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OBSIDIAN CLIFF,
YELLOWSTONE NATIONAL PARK.

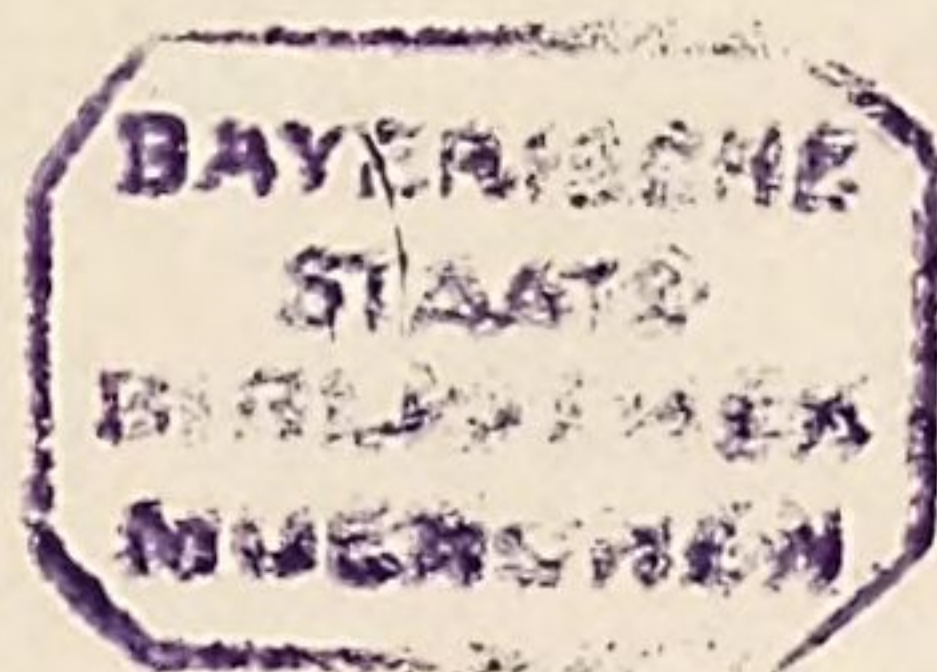
BY

JOSEPH P. IDDINGS.

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OBSIDIAN CLIFF YELLOWSTONE NATIONAL PARK.

BY JOSEPH P. IDDINGS.

INTRODUCTION.

The tourist who, in his wanderings in search of entertainment, adventure, or health, has been so fortunate as to visit the great National Park vividly recalls how, on the first day's ride from the Mammoth Hot Springs to the geyser basins, after traveling up the picturesque road along Glen Creek, at the northern base of Mount Bunsen, to Rustic Falls, he came upon Swan Lake Valley and beheld for the first time the grand and imposing peaks of the Gallatin Mountains, which extend from Electric Peak, 11,000 feet in height, southward to Mount Holmes, with an altitude of 10,300 feet. After driving over open country to the crossing of the Gardiner River and through the flat-bottomed valley known as Willow Park, he entered the timber and rode along the west bank of a narrow stream, which fights its way through grass and fallen trees, until he reached the northern end and outlet of Beaver Lake. On his left, to the east, stretches a long, low cliff, the southern end of which is formed of nearly vertical columns of black obsidian, or volcanic glass, which has resulted from the rapid cooling of a perfectly fused, igneous rock. From this great blocks have fallen and accumulated at its base in a talus slope, over which has been built what is popularly known as the glass road, the material of which it is made being as true a glass as any artificially produced. The colors and structure of this natural glass not only make it the most interesting rock the visitor will find, but the phenomena of its occurrence in this locality are of special scientific importance, and the present paper has been prepared with the view of describing and explaining it.

GEOLOGICAL OCCURRENCE.

Obsidian Cliff is at the northern end of Beaver Lake, in the Yellowstone National Park, about eleven miles south of Mammoth Hot Springs. It forms the eastern wall of a narrow cut in the plateau country through which Obsidian Creek flows at an elevation of 7,400 feet. The cliff extends for half a mile, rising from one hundred

and fifty to two hundred feet above the creek and falling away gradually to the north; the upper half is a vertical face of rock, the lower portion a talus slope of the same material. Back of the cliff to the east the country rises in a series of rude benches to about four hundred feet above Beaver Lake; at this level, a little south of Obsidian Cliff, the edge of the plateau forms a small cliff fifty feet high, above a long, steep slope east of the lake. From here the top of the plateau rises in hillocks and basins eastward to an altitude of about eight thousand feet above sea-level. On the opposite side of Beaver Lake and Obsidian Creek abrupt hills slope up to the plateau country west. The whole region in this vicinity is thickly timbered with a small growth of pines.

The cliff presents a partial section of a surface flow of obsidian which poured down an ancient slope of rhyolite from the plateau lying to the east. The underlying rhyolite has a purplish-gray color and is readily distinguished from the black obsidian, as well as from the lithoidal portions of the obsidian flow, by the abundance of porphyritic crystals of quartz and feldspar which fill the older rock, the later flow being entirely free from them. The older rhyolite is not exposed beneath the obsidian along the creek, but is first met with in the edge of the timber south of the end of the cliff, where a narrow drainage channel has cut into the slope. This rhyolite rises higher to the south and forms the long slope east of Beaver Lake, above which is the low cliff already mentioned. This cliff is of obsidian, which is exposed in a vertical section of more than fifty feet. Following the obsidian back from the face of this cliff up the hummocky surface it becomes filled with gas cavities and passes into banded, pumiceous rock and finally into light-gray pumice. This covers the surface of the plateau for two and a half miles eastward to the valley of Solfatara Creek, which drains into the Gibbon River; here, again, the lava flow is exposed in a cliff the lower portion of which is black and red obsidian. Toward the south the obsidian flow extends for a mile beyond the Lake of the Woods, and northward across the east and west drainage, which cuts off the higher portion of the plateau, a distance of some five miles.

What was the original thickness of this lava sheet it is not possible to say. The dense glass, or obsidian, forming the lower portion is from seventy-five to one hundred feet thick; the porous and pumiceous upper portion has suffered more or less erosion, which was in part the result of ice action, the evidence of glaciation being more marked along the lower western slope of the plateau than on the top of it. The surface of the plateau is mostly pumice, with little if any glacial debris scattered over it, but along the western slope the rock has been worn down to the massive obsidian, and the top of the cliff is covered with planed and striated glacial drift from a great variety of sources.

Half a mile southeast of Obsidian Cliff, on the plateau, about five hundred feet above the level of Beaver Lake, is a circular pit 100 feet deep, the mouth of it being 300 feet wide by 350 feet long; its sides stand at an angle of 35° and appear to be formed of pumiceous obsidian, the angular masses in the bottom being pumice. The rim of the pit does not rise above the level of the surrounding surface, and one comes upon it quite unexpectedly in the timber. The general appearance is that of a small crater which has been but slightly affected by glaciation.

Near by to the south is a short, narrow ridge of porous obsidian, rising two or three feet above the general surface. The ridge curves considerably and is cracked along its center. The only other surface features characteristic of a lava flow which are found in this vicinity are several small basins with obsidian rims; one is 20 feet long by 10 feet wide and about two feet deep, and within it at one end is a smaller basin, six by three feet.

The exact point at which this obsidian broke through the older rocks and reached the surface has not yet been discovered; but that forming Obsidian Cliff has evidently flowed down from the high plateau in a northwest direction into a pre-existing valley, the planes of flow in the lava clearly indicating that it has crept down the slope back of Obsidian Cliff and accumulated in the bottom of a channel between rhyolite hills. This old channel was just east of that occupied by Obsidian Creek, which has cut its way along the contact between the rhyolite to the west and the obsidian. This is shown by the fact that the general bedding or flow structure of the columnar portion along the face of the cliff dips slightly to the east away from the western body of rhyolite.

LITHOLOGICAL STRUCTURE.

COLUMNAR CRACKING.

Obsidian Cliff is especially remarkable for the development of prismatic columns, which form the southern end of the mass. Such columns are of common occurrence in basalt the world over, the most familiar localities being the Giant's Causeway and Fingal's Cave, on the coast of Ireland. There are others in central France and Germany and throughout the great volcanic area in western North America, especially along the Columbia River and in the Yellowstone Park; they are in almost every basalt flow in fact, so that columnar structure is often erroneously termed basaltic structure. But columnar structure is by no means confined to such rocks, being found in all varieties, from the basic to the acidic, though less frequently in the latter. Columnar structure is well developed in the rhyolites of the Yellowstone Park. Instances of its occurrence in obsidian, however, are exceedingly rare, and in the obsidian flow under considera-

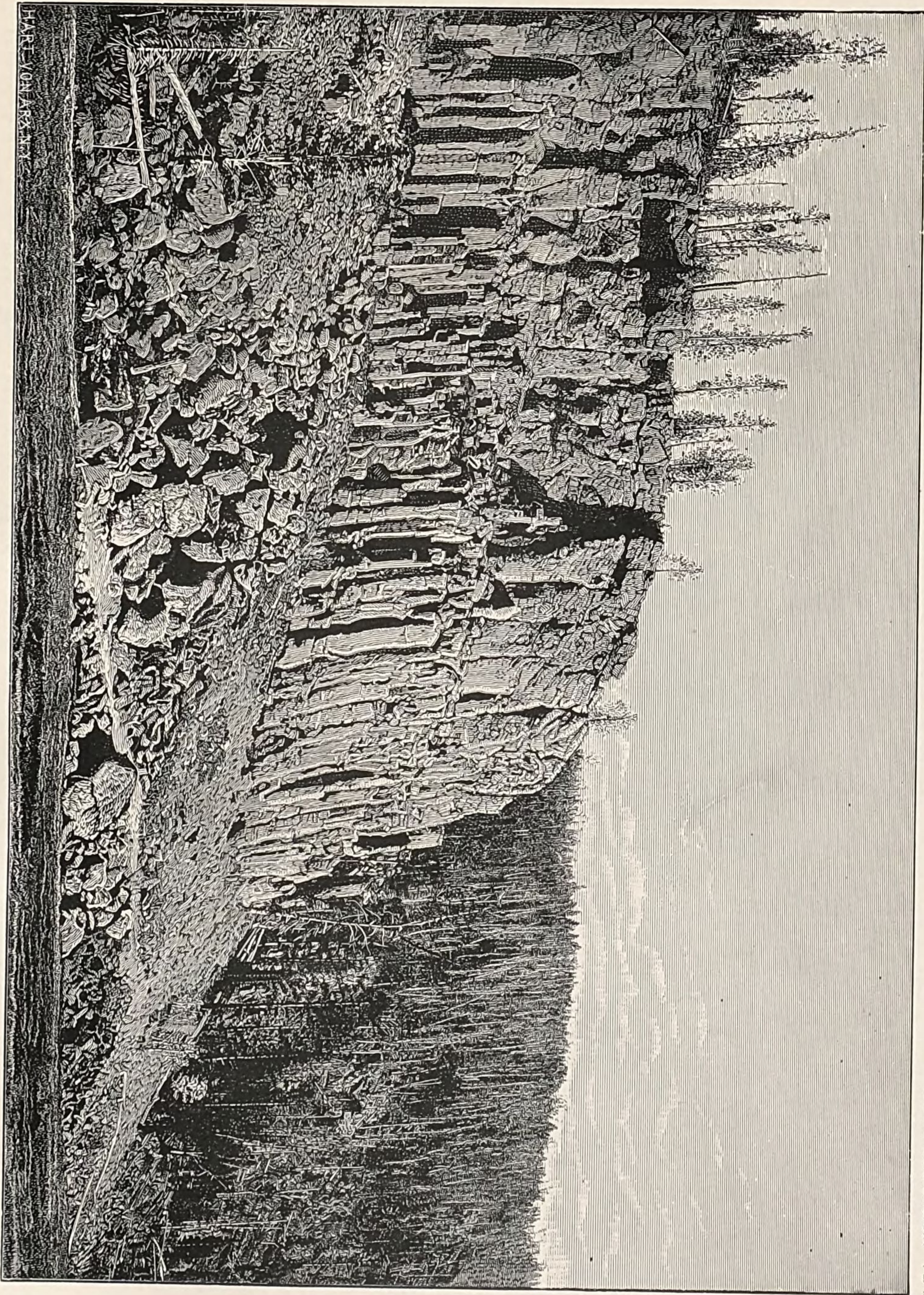
tion it is confined to a small area, several hundred feet in extent, in that portion which poured into the old channel and acquired a greater thickness than that of the main flow.

A view of the west face of the southern end of the cliff is given in Pl. IX. The shining black columns rise from a talus slope which reaches some fifty feet up the cliff. These prisms are fifty or sixty feet high and vary in width from two to four feet near the end of the cliff, the width of each column being quite constant throughout its length. On the south face of this end of the cliff the columns are the same, but grow less clearly defined toward the east, where a sharp bend in the lava sheet has formed gaps in the rock and destroyed the continuity of the mass; beyond this the columns incline considerably toward the west, as though the underlying surface of contact sloped toward the west also. Farther up the slope to the east they disappear. The columns in the main face of the cliff are tilted 10° to the eastward, and the planes of flow which cross them have an average dip of 10° east, indicating that the underlying surface at this place slopes toward the east. Along the cliff to the north the columns become gradually broader, the largest being 20 feet in width.

The prisms have no uniform number of sides, four, five, and six being those most frequently observed; the sides are unequally developed, but at a distance the general effect is quite regular. Toward the north, with the change in the nature of the rock, to be described later on, the broad columns grade into massive blocks formed by vertical cracks much farther apart.

The rock forming the lower part of the columns is dense, black obsidian, with thin, lithoidal bands or layers of small spherulites, which are round, stony bodies, resembling hazel-nuts, or sometimes clay concretions. They have a radially fibrous internal structure and will be fully described (see p. 14). In this part of the columns there are almost no cavities or lithophysæ, as the hollow forms of spherulites are called, and but little contortion of the layers. Higher up, the rock is less massive and contains large lithophysæ flattened in the plane of flow. The tops of the columns pass into massive obsidian, which for 10 feet is quite dense, but above is full of large cavities which fairly honeycomb the mass. This may be seen on Pl. X, engraved from a photograph taken near the base of the columns, which, though nearly vertical, appear considerably inclined and distorted in the picture.

This upper portion, about fifty feet thick, is divided by vertical cracks into broad, quadrangular blocks having no resemblance to columns. The sides of the columns are comparatively straight and are independent of the flow structure within the mass, which is indicated by the microscopic banding of the obsidian and by the layers of spherulites which traverse the rock in parallel planes. The



SOUTHERN END OF OBSIDIAN CLIFF.



OBSIDIAN COLUMNS.

bending and twisting of these show the contortion of the viscous lava just before it came to rest. These layers pass through the columns at all angles, often showing abrupt folds and curves, which have been cut across sharply by the prismatic cracks. The crystalline layers formed planes of weakness through the rock, which has parted along them, producing transverse cracks that bear no fixed relation to the direction of the prisms, but follow the deviations of the flow. The contortion of the lava is particularly noticeable along the south face of the cliff, where the nearly horizontal layers in the most westerly columns curve upward and pass nearly vertically out of the present top of the cliff. Still farther to the east the layers are greatly twisted. At one place vertical rents and gaps between the layers show that the molten glass was so viscous and stiff before it finally came to rest that it pulled apart where the layers were vertical and did not close up again before the lava solidified.

The columnar portion on the west face extends for only a few hundred feet, the nature also of the rock changing in this direction. The lithoidal and spherulitic layers become more frequent until the black glass appears only in thin bands between light-gray layers, finally being represented by dark-gray lines between those of lighter color. This transition takes place in ascending the face of the cliff toward the northern end of the columnar portion, and also horizontally, the great bulk of the lava farther north, where the cliff is 200 feet high, being a light-gray, lithoidal rock, thinly fissile parallel to the planes of flow and bearing no resemblance to obsidian. In places through it black and red glass occurs in considerable quantity, mostly near the upper part of the cliff. The lithoidal form of the rock is not found in other parts of the sheet where it is one hundred feet and less in thickness, but only where it reached a much greater depth by filling up the old valley already mentioned. Unfortunately there is no indication of the original thickness of the lava at this place, as the top has been planed down by ice action and very considerably lowered. It is divided by two systems of vertical cracks into great quadrangular blocks which form a bold cliff rising 100 feet above the débris slope, a view of which is shown in Pl. XI.

As previously noticed, the columnar obsidian is only found in a small portion of that part of the lava that poured into a depression and acquired a greater depth than that of the flow in general, which is often 100 feet thick. The columnar portion was something over one hundred and sixty feet deep, but probably less than that of the lithoidal part farther north, where the mass cooled slowly enough to permit crystallization. The exceedingly rare occurrence of columnar structure in obsidian is probably owing to the fact that the conditions favorable for the production of prismatic structure and also for the solidification of the lava as amorphous glass are seldom coincident, the cause of columnar structure being unquestionably the shrinkage of a homogeneous

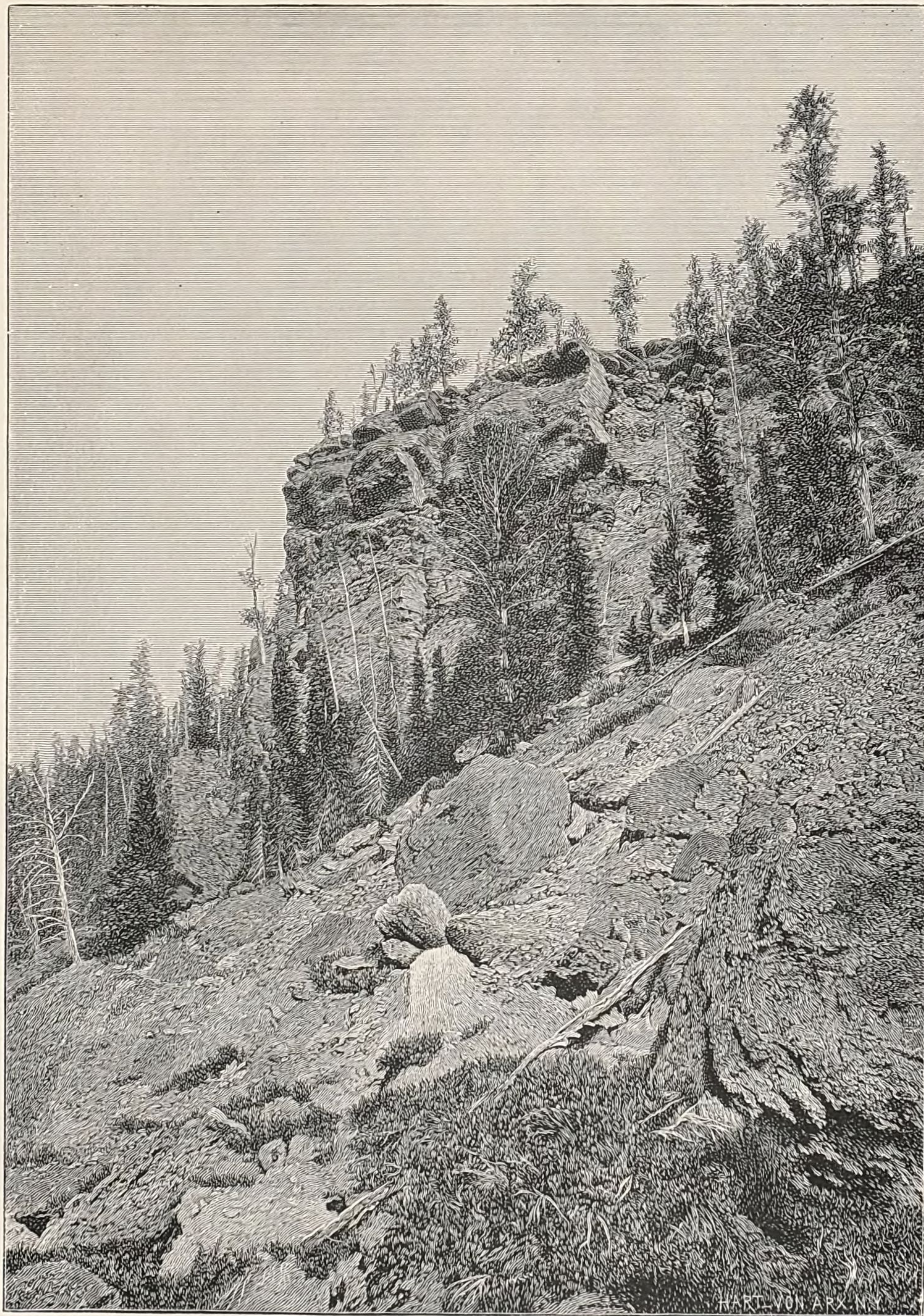
rock which is cooling at a moderate rate from its surface. The very rapid surface cooling of a molten rock tends to produce cracks parallel to the surface,¹ and cracks normal to the surface appear only in that portion of the mass which cools more slowly, the rate of cooling and the nature of the rock affecting the size of the columns, which are larger as the cooling is slower. The internal micro-structure of this obsidian and the fact that the spherulites and lithophysæ are cut sharply across by the planes of the cracks prove that the glass was rigid before the columns were developed. In general the obsidian shows but little tendency to crack, even where it has cooled rapidly, and in many parts of the flow no particular system of cracks is observed.

LAMINATION.

If the cooling rock is not homogeneous in composition or texture the results of contraction will be altogether different. This is illustrated at the northern end of the cliff, where the lithoidal rock is traversed by widely distant, vertical cracks and a multitude of nearly horizontal ones which follow the planes of flow through all their complexities. The latter have resulted from differences in texture of the alternating layers, the most probable cause of which differences will be suggested later.

The origin of lamination or layer-structure frequently observed in many lava flows and so strikingly developed in the lithoidal portion of Obsidian Cliff is readily understood from the following: In a fluid free to flow over a horizontal surface the movement of the molecules will meet with least resistance in directions parallel to the plane of that surface; the fluid will therefore spread horizontally in all directions, producing a movement of its molecules in planes parallel to the underlying surface. Particles suspended in the fluid will be carried along these planes and portions differing in the amount or character of the suspended matter will be drawn out into layers along these planes of flow. In the case of lavas, the production of such layers will depend on the viscosity and lack of homogeneity of the mass at the moment of eruption and on the distance it flows. In the more liquid and homogeneous lavas, such as basalt, evidence of internal flow or lamination is less marked than in the more viscous and less homogeneous acid lavas, as rhyolite, where slight variations in the consistency of the mass find expression in bands and streaks of color or in layers of differing micro-structure and degree of crystallization. The greater the distance over which a viscous lava has spread, the thinner will be the layers of different consistency, which, near the source, may have been lenticular or quite irregularly shaped portions.

¹ The columnar structure in the igneous rock on Orange Mountain, New Jersey, J. P. Iddings: *Am. Jour. Sci.*, 3d series, vol. 31, 1886, pp. 321-331.



CLIFF OF LITHOIDAL RHYOLITE.

PETROGRAPHICAL CHARACTER.

OBSIDIAN.

Approaching nearer the cliff and climbing over the masses of rock which lie at its base we shall find our interest increasing as the great beauty and variety of the lava are disclosed. At the southern end, where the road passes beneath the columns, the greater part of the rock is black, lustrous glass, or *obsidian*, so named after Obsidius or Opsius, its discoverer, in Ethiopia, according to Pliny, who says that when inlaid in chamber walls in the form of mirrors it reflects shadows instead of images. He also states that the ancients made signet stones of it.¹

King, in the work just cited, calls attention to the fact that the Peruvians also used the same stone for mirrors.

When broken it flies into sharp, angular fragments, with razor-like edges which are quite transparent and colorless in the thinnest places. It is this quality of the stone, together with its hardness, very nearly that of quartz, which makes it a favorite material for use as knives, spearheads, and arrowpoints by semi-civilized people. It was in common use among the Aztecs at the time of the conquest of Mexico by the Spaniards, as we learn from Prescott,² who, in describing the various implements used by these people, says:

They employed another tool, made of itztli, or obsidian, a dark, transparent mineral, exceedingly hard, found in abundance in their hills. They made it into knives, razors, and their serrated swords. It took a keen edge, though soon blunted. With this they wrought the various stones and alabasters employed in the construction of their public works and principal dwellings (p. 143).

Their weapons were slings, bows and arrows, javelins, and darts. * * * These various weapons were pointed with bone or the mineral itztli (obsidian), the hard, vitreous substance already noticed as capable of taking an edge like a razor, though easily blunted. * * * Instead of a sword they bore a two-handed staff, about three feet and a half long, in which, at regular distances, were inserted, transversely, sharp blades of itztli—a formidable weapon, which an eye-witness assures us he had seen fell a horse at a blow (p. 433).

Another character of obsidian, which it shares with other homogeneous glasses, is the shelly or conchoidal fracture which is developed when it is broken by the blow of a hammer, the undulations of the surface of fracture spreading in arcs of concentric circles around the point of concussion. Occasionally the fracture takes the form of a cone, whose apex is at the point struck. Still more rarely a natural spherical sundering is observed, where thin layers like those of an onion encase a solid nucleus.

The color of this obsidian for the most part is jet black, but much of it is mottled and streaked with bright brownish red and various shades of brown, from dark to light yellowish brown, purplish brown,

¹ C. W. King : The Natural History of Gems, London, 1867, p. 209.

² William H. Prescott : History of the Conquest of Mexico, vol. 1, Phila., 1874.

and olive green. The brilliant luster of the rock and the strong contrast of these colors with the black are very striking. In places the glass has been broken into small, angular pieces and cemented together, producing a many-colored and beautiful breccia. Some of the obsidian shows a fine, satin luster in certain positions. This is produced by the reflection of light from the walls of long, slender gas cavities which fill that portion of the glass that approaches the surface pumice. Another luster is occasionally exhibited in deeper-seated obsidian; it is a golden sheen which under a lens resolves itself into thin beams of red and yellow light, apparently reflected from minute cracks along the surface of microscopic shreds of brown and yellow glass.

SPHERULITES.

Through the black and red glass are scattered dull, bluish-gray patches and bands and round, gray and pink masses, looking like concretions, some of them being hollow or porous. The effect of these spherulitic forms is still further to vary the appearance and beauty of the rock and to make it the most conspicuous and characteristic variety of volcanic lava known. Similar spherulitic obsidian occurs in many parts of the world, notably in the Lipari Islands in the Mediterranean, in New Zealand, Mexico, and the western United States. The last-named occurrence will be more particularly noticed at the end of this paper. Owing to the great variety and the freshness of the spherulites and the perfection and beauty of the lithophysæ occurring at Obsidian Cliff, as well as to the interesting results derived from a careful study of them, they will be described with considerable detail, in order to give a clear idea of their structure and composition.

The simplest forms of the macroscopic spherulites — that is, those visible to the unaided eye — are small, dark-blue spherules about the size of a mustard seed, embedded in the black obsidian. When broken they appear lighter gray within, have a dense, porcelain-like texture, and show slight indications of a radially fibrous structure. They are mostly located along fine lines of minute punctures on the surface of the obsidian. The small, blue spherules are generally crowded together along these lines, or more properly along the planes of which these lines are the traces, the layers of spherules agreeing in all their bending and contortions with the fundamental planes of internal flow in the glass. A number of layers will sometimes lie close together, with the thinnest possible sheet of black glass between, or they will unite in a band a quarter of an inch or more thick, whose surface is covered with protruding hemispherules. Isolated clusters of blue spherules occur, making compound spheres, and more rarely these groups are prolonged in one direction, forming parallel ropes through the black glass.

The surfaces of the spherules are often brown or red and constitute planes of weakness between the spherules and inclosing glass, along which the two frequently separate with ease, leaving a dull, pitted surface on the obsidian. The arrangement of the spherules in the plane of flow is then seen to be quite irregular, though occasionally in arborescent figures.

Spherules about the size of peas have an agate-like banding in concentric shells, combined with a radially fibrous structure. Their form is more or less spherical, sometimes being depressed on one side and looking like miniature tomatoes or else prolonged into oblong gourd shapes. More frequently they are aggregated in botryoidal and kidney-shaped forms. Their surface, when relieved of the obsidian, has a delicate, velvety bloom like a peach, which in rich shades of brown and terra-cotta contrasts finely with their black, glassy matrix.

The larger spherules, an inch or more in diameter, are mostly lighter colored, in various shades of reddish gray, sometimes with a blue center. They appear of a more earthy texture than the small ones, but have a fine, radially fibrous structure, with a satin luster; in some cases there is a granular, spotted appearance toward the outer portion, and frequently a distinctly concentric structure is present, the shells being either broad and dense or of the most delicate thinness. The surfaces of these spherules are often ribbed with rings running parallel to the flow planes of the rock, closely resembling the surface of concretions in sedimentary rocks. Their shapes vary from spheroidal to flattened disks and hemispheres, and are also in irregular sectors and plume-like forms produced by the interference of spherules growing close together.

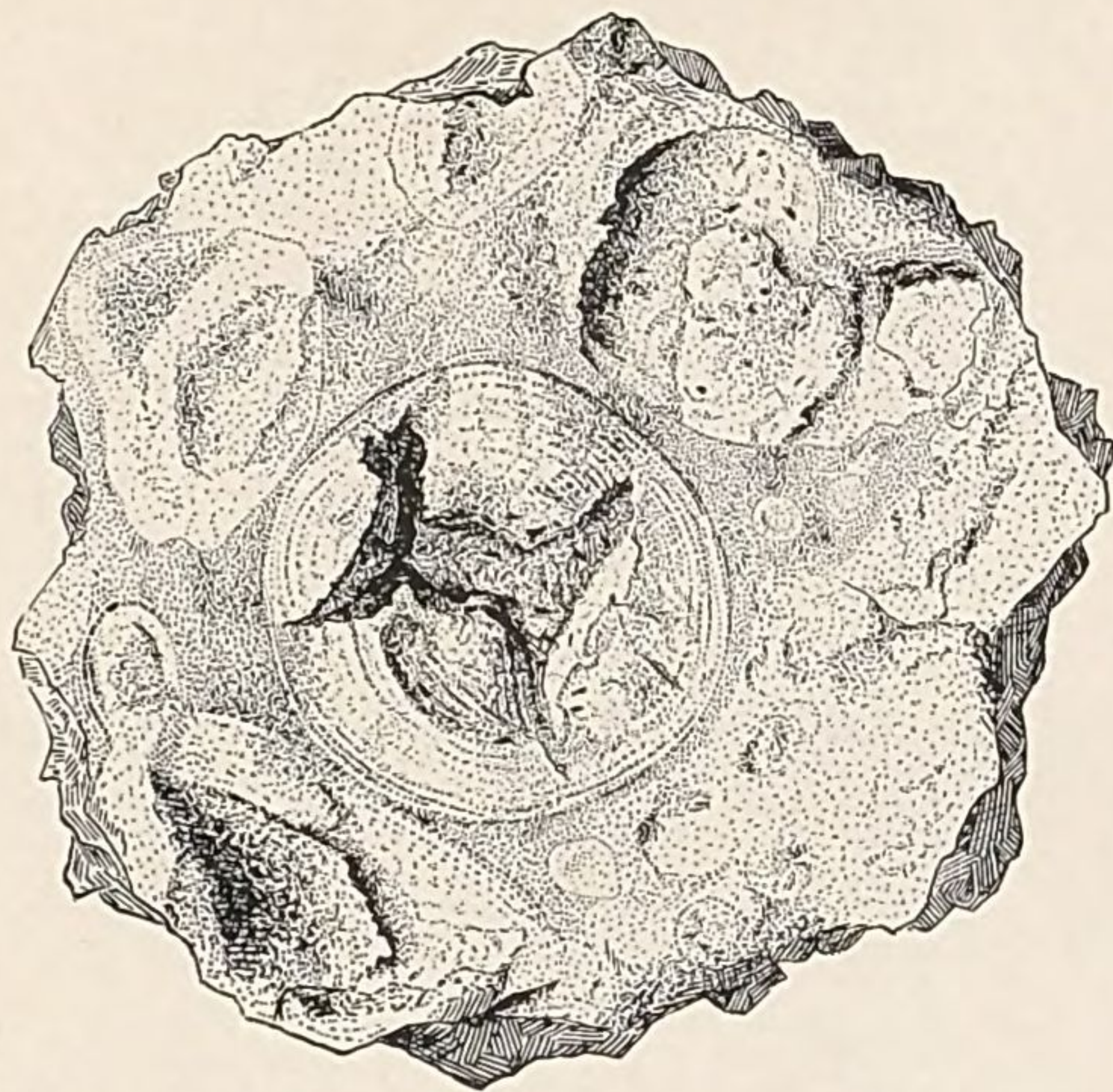
Through all these spherules, large and small, run delicate lines of banding parallel to and in continuation of the planes of flow inherent in the rock; sometimes they are only recognizable with the aid of a lens. This indicates that the spherules were developed in the glass in the same relative positions they now occupy; that is, they must have been formed after the lava came to rest. Frequently the largest spherules were formed earlier than the smaller ones, but this is by no means a fixed rule, for large, red hemispherules have often developed on a layer of small, blue ones, and discoidal ones between such layers.

Hollow spherulites.—Finally, the spherules are not all solid, the larger ones not at all so. Those looking earthy and densest have microscopic spaces between the fibers and grains composing them. Others have a fine granular appearance and glisten from the crystals of which they are made up. Most of them have porous or open cavities within their mass, the periphery often forming a solid shell or crust like the rind of a cantaloupe. These cavities ramify through the heart of the spherule and are coated with brilliant crystals. The porous spherules resemble pithy berries, while the central mass of

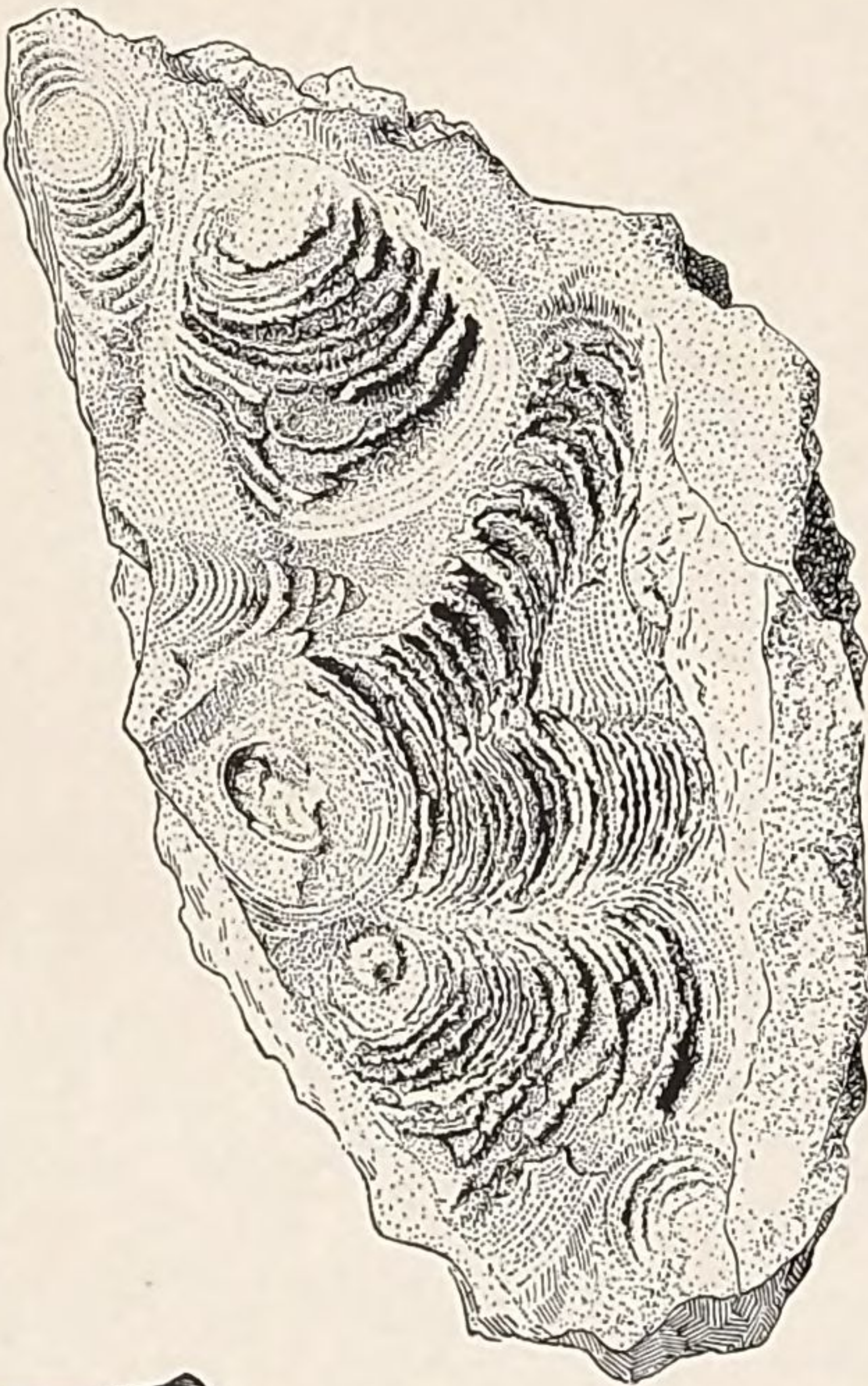
the more open ones appears to have shrunk and cracked apart like the heart of an overripe watermelon. This is shown to a certain extent in Pl. XII, Figs. 1 and 5. The fibers and nodules of the mass are often very distinct and coarse and its color is nearly white. In many cases the cavity is confined to the limits of a single spherule, detached ones with perfectly solid exteriors being often hollow within. The isolated spherules in dense, black obsidian without the microscopical trace of cracking are sometimes half hollow, presenting the purest white skeleton of fibers and nodules, or consist of concentric, crystalline shells dotted with minute pellets. This form is represented in Pl. XII, Fig. 3. The shells are usually so delicate that parts of them are loosened and fall out when the obsidian is broken. On the white and beautifully frosted substance of these hollow spherulites rest the honey-yellow crystals of fayalite, as yet unattacked by atmospheric agencies. Cavities are less frequent in the small, blue spherules, though occasionally the smallest are white and porous, and along the spherulitic layers or through the black glass run crinkled bands of small cavities, or porous layers, with a white, gray, or pink coating.

LITHOIDITE.

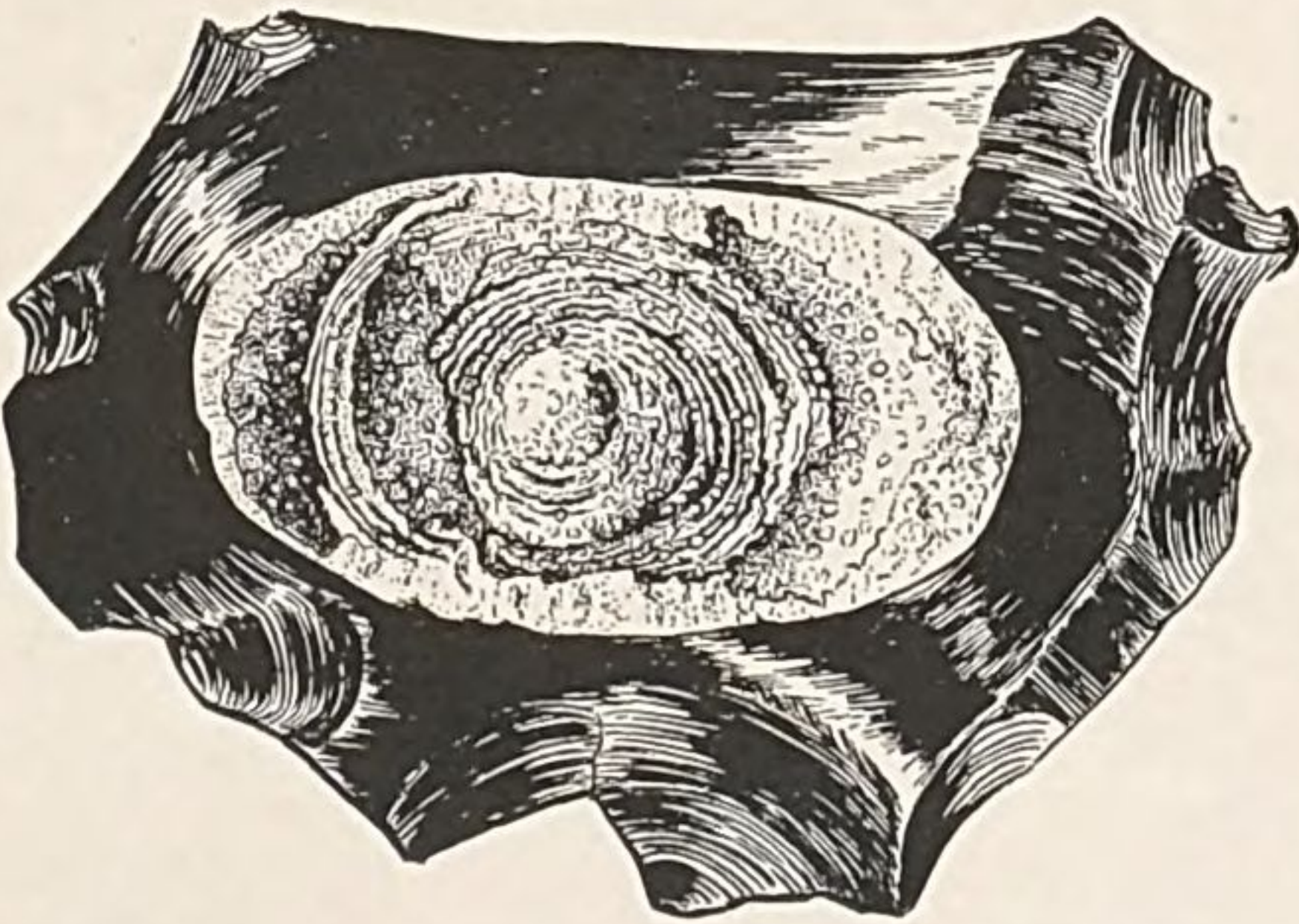
Besides the thin, blue layers with spherulitic structure, occurring in the obsidian, there are light-gray ones of a more crystalline or porcelain-like nature. As these become more frequent the rock assumes a lithoidal or stony appearance and grades into purplish-gray rock, finely banded with blue, having occasional layers of black obsidian running through it. At the northern end of the cliff, as already noticed, there is very little black glass left and the rock is an excellent lithoidal rhyolite or lithoidite. This lithoidite is a light purplish-gray rock, which shows, on cross-fractures, delicate bands of light and dark colored layers. The former are crystalline, with small cavities scattered along them, which form planes of weakness and permit the rock to split into thin plates often one-sixteenth of an inch in thickness. The dark layers are microspherulitic and dense, showing in many cases a system of fine parallel cracks, all of them running in one direction and perpendicular to the plane of the layer. These cracks are at quite uniform distances apart in any one layer, usually half an inch and less, being closer together the thinner the layer. Upon examination it is seen that the direction of the cracks is at right angles to the streaks of color in the rock, which mark the direction of flow. From this position of the cracks, which are the result of the shrinkage of the rock upon cooling and which must lie at right angles to the direction of maximum strain, we see that along the line of flow at the time of consolidation the tension was greater than in other directions, which was probably due to a pulling stress exerted in that part of the lava sheet that stretched down



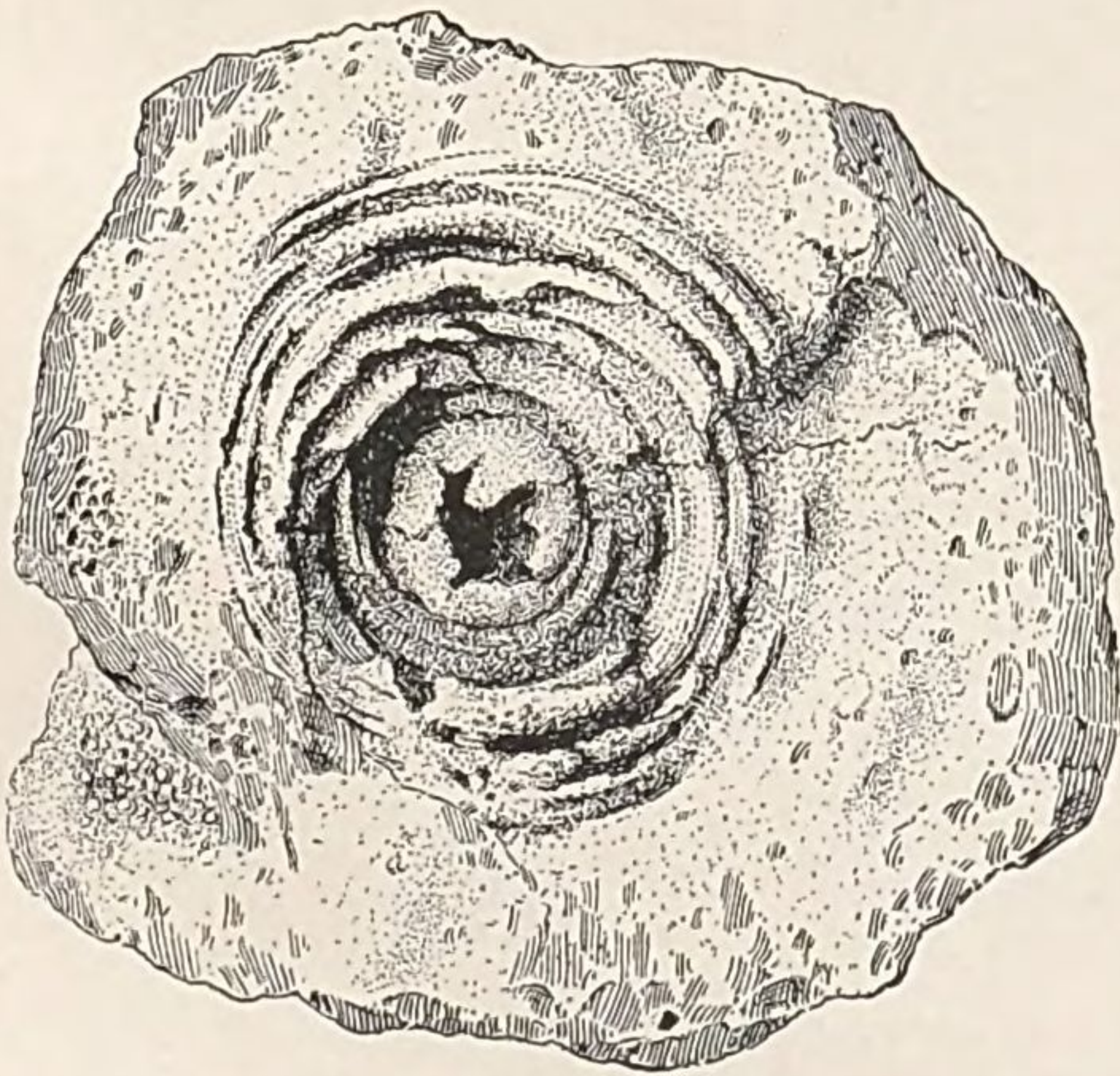
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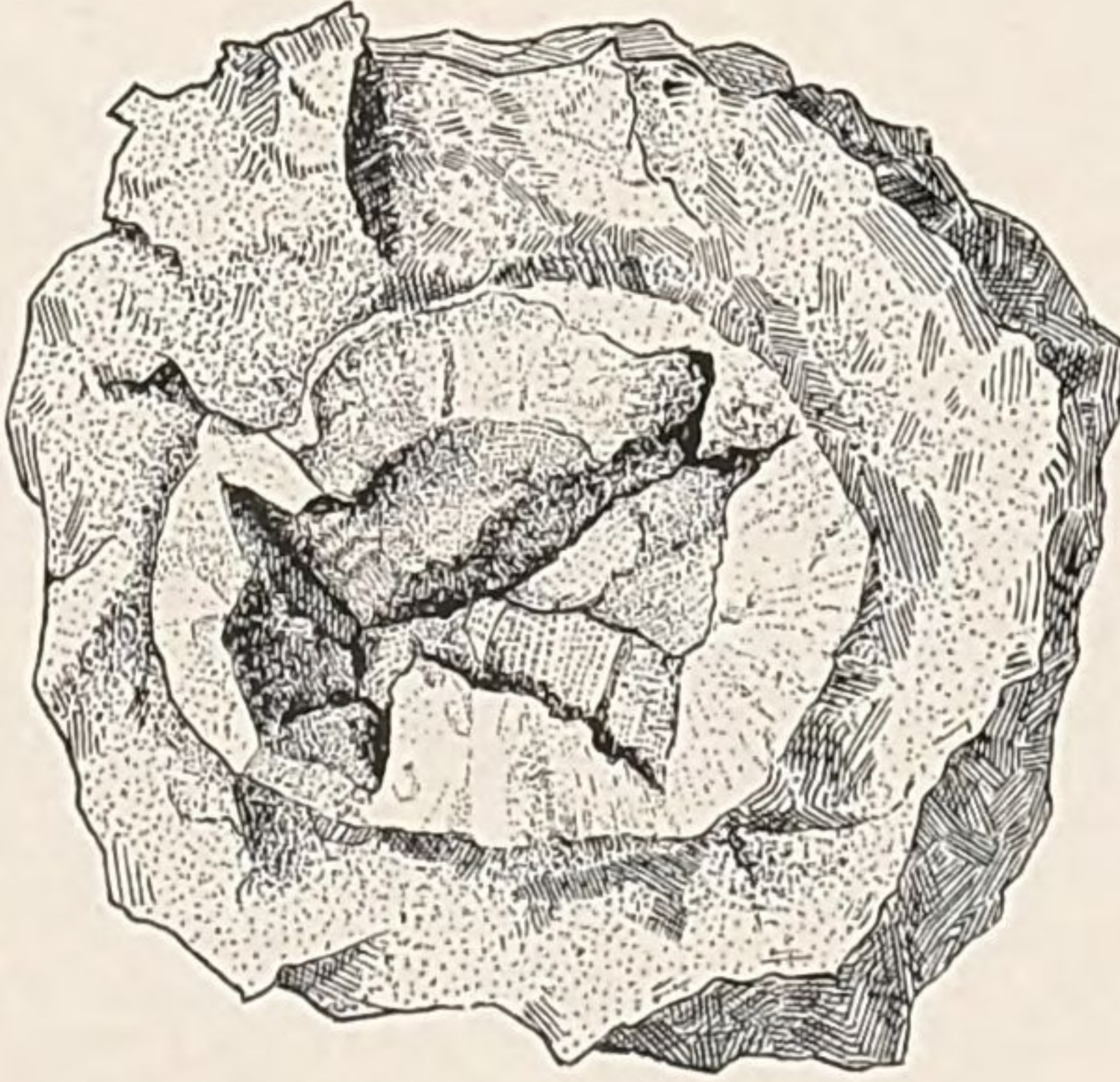
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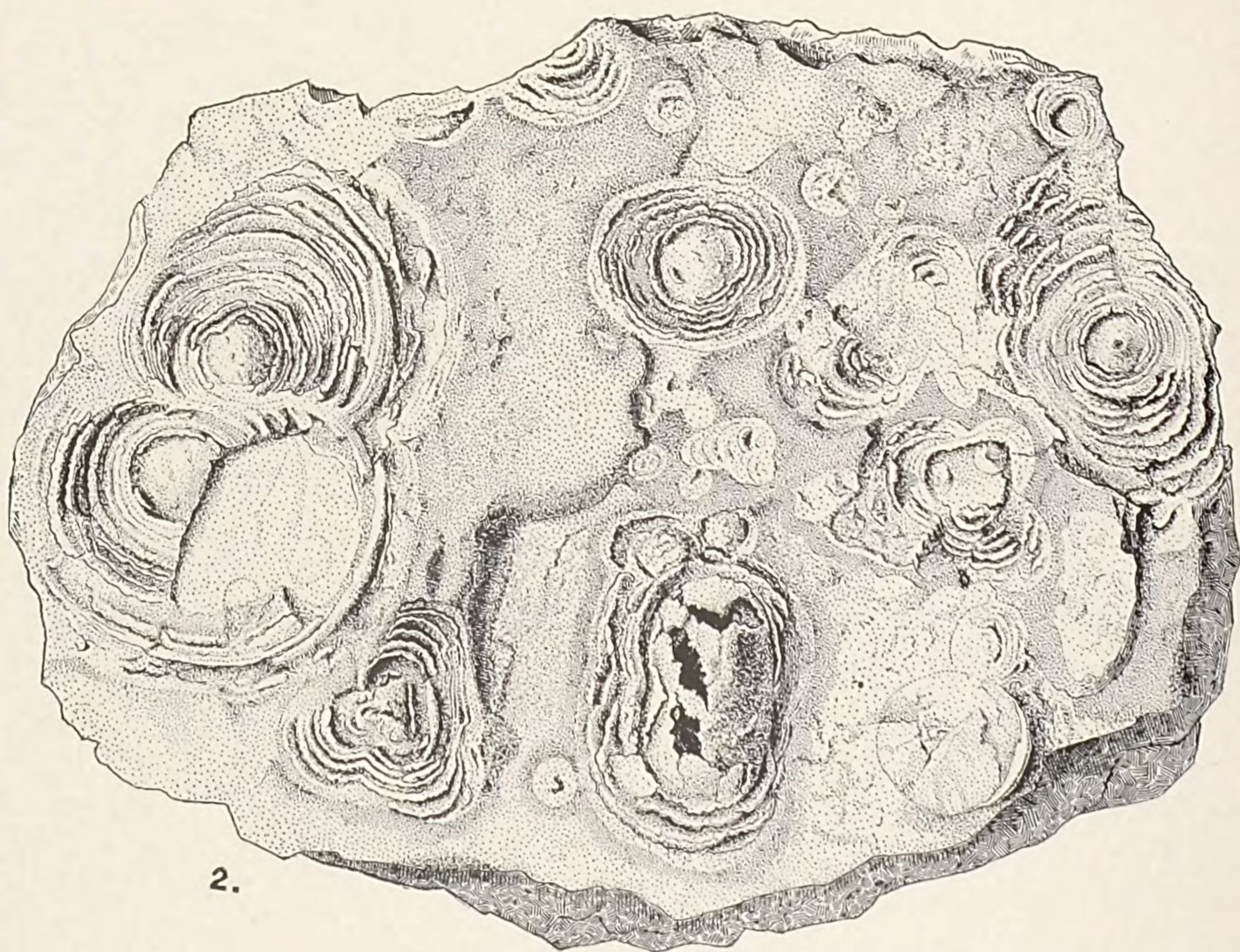
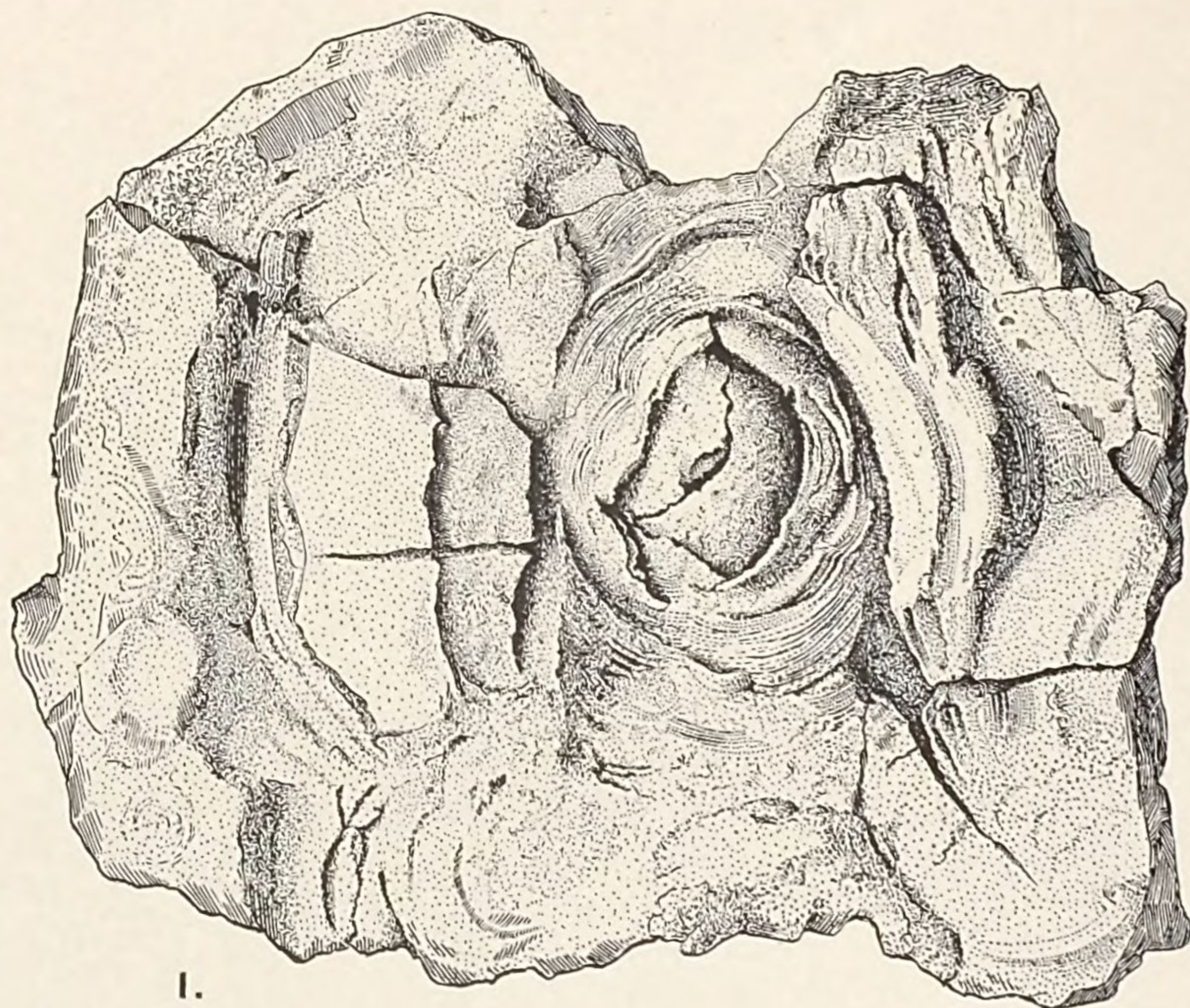
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LITHOPHYSÆ IN THE LITHOIDITE OF OBSIDIAN CLIFF, NATURAL SIZE.

the slope from the plateau above. In places the rock breaks into blocks which bear so striking a resemblance to silicified wood that one is easily deceived at a little distance.

LITHOPHYSÆ.

The lithoidal rock is as full of spherulitic forms as the obsidian, but it appears more porous and contains a multitude of hollow spherules of the utmost delicacy and beauty. An idea of their great abundance is given by Pl. XIII, Fig. 2, which was drawn from a slab of lithoidite and is the natural size. Most of them are hemispherical and consist of a group of concentric shells which curve one over another like the petals of a rose (Pl. XII, Fig. 4, and Pl. XIII, Fig. 1). The shallower ones present small, rose-like centers surrounded by thin, circular shells (Pl. XIII, Fig. 2). The disks are sometimes oval and sometimes composed of several sets of shells which have started from centers near together and developed in sectors, giving a scalloped form to the curves (Pl. XIII, Fig. 2). Others are eccentric or send out long, curving arms, cross-walled like a chambered ammonite (Pl. XII, Fig. 2).

The partition walls are generally very thin and often close together, in one instance fifty occurring within a radius of two inches. They are very fragile and crumble under the touch, being made up of small and slightly adhering crystals with brilliant, glistening faces.

A fine example of a lithophysa is shown on a natural scale in Pl. XIII, Fig. 1. The rose-like center is surrounded by delicate shells. Those outer portions to the right and left which still remain are somewhat massive, though finely porous and crystalline, and are traversed by well marked shrinkage cracks. The contraction of the massive portions is clearly indicated by these cracks, which gape open from the base to which the substance of the lithophysa adhered. The largest forms are a foot or more in diameter and are very suggestive of wasps' nests.

These hollow structures have been called *Lithophysen* by von Richthofen,¹ because the rock appears to have been inflated or expanded like bubbles. He described those found in the rhyolites of Hungary and considered that the viscous rock had been expanded by steam. A review of his observations on their nature and origin will be given in its proper connection.

But these lithophysæ cannot be considered as having been actually expanded by gas or steam, however much they resemble the bursting bubbles which rise to the top of boiling mud, a sight familiar to all who visit the Yellowstone region. They bear an intimate relation

¹ Studien aus den ungarisch-siebenbürgischen Trachytgebirgen: Jahrbuch k. k. geol. Reichsanst., vol. 11, 1860, p. 180.

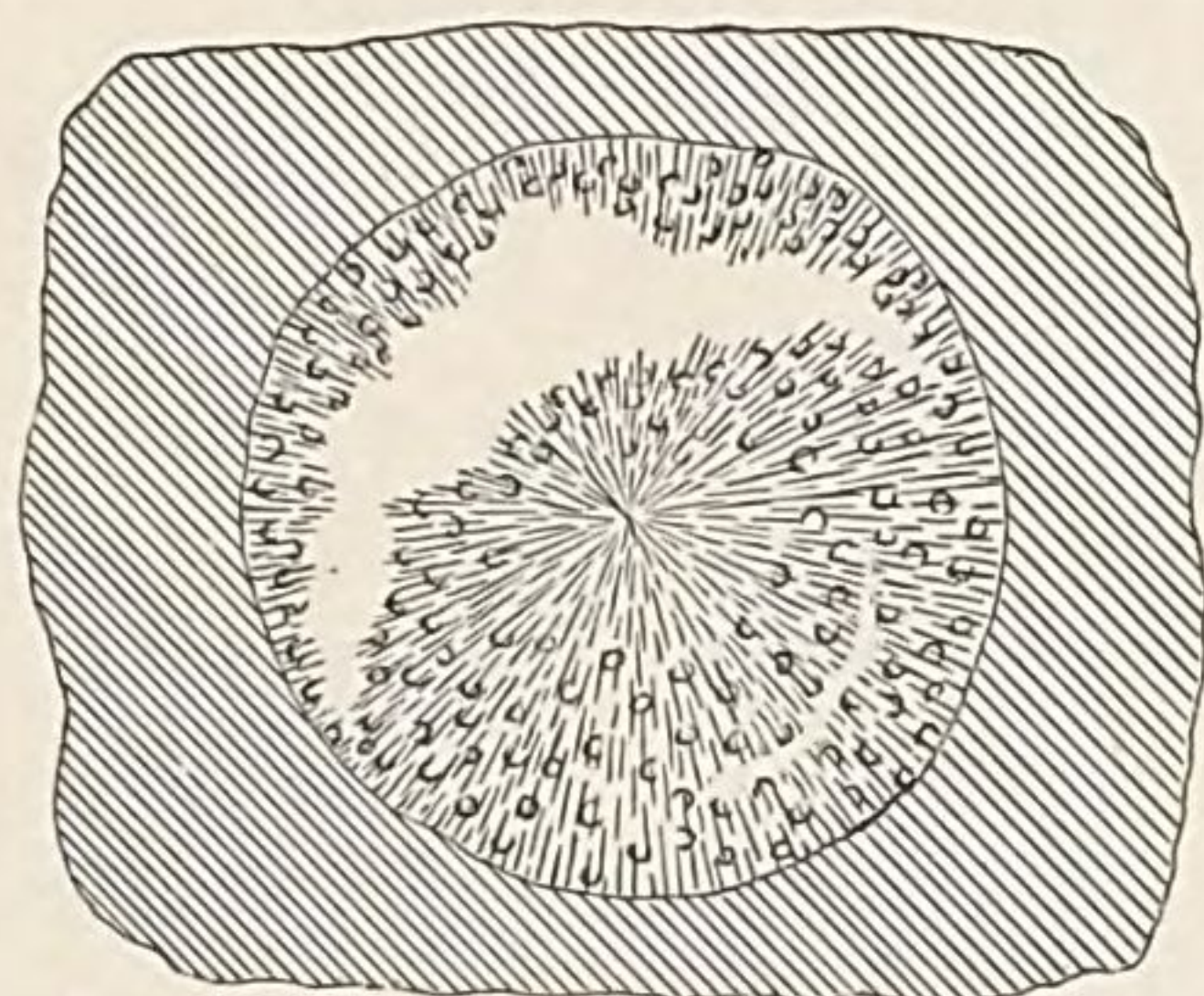
to spherulites, as the stone spherules are called, which becomes evident upon comparing the various structures exhibited by each.

Corresponding to the complete spherulite with simple, radially fibrous structure and no concentric banding, there are similar spherulites partly hollow at the center or irregularly so through their mass, as in Pl. XIV, Fig. 1. The simple spherulite which is traversed by parallel bands, in continuation of the planes of lamination in the rock, has a corresponding porous form, in which these bands become partition walls between the porous or hollow portions (Pl. XIV, Fig. 2). Spherulites with concentric banded structure have more or less hollow varieties where the denser bands remain as thin shells coated with crystals (Pl. XIV, Fig. 3), and among these are some crossed by the parallel bands of flow structure, which are clearly recognized in the hollow forms (Pl. XIV, Fig. 4). The hemispherulite with concentric bands, when developed in a narrow layer of glass, spreads out in the shape of a flattened disk, the bands farthest from the center being only short arcs of circles. The hollow form corresponding to this is the most characteristic lithophysa found in the lithoidite of Obsidian Cliff, which has already been described and is shown in cross-section in Pl. XIV, Fig. 5. Lithophysæ intersected by the bands of lamination of the matrix also occur (Pl. XIV, Fig. 6), the two systems of delicate walls being distinctly independent of each other. Finally, partial spherulites in the shape of sectors and plume-like forms are represented among the irregularly developed lithophysæ.

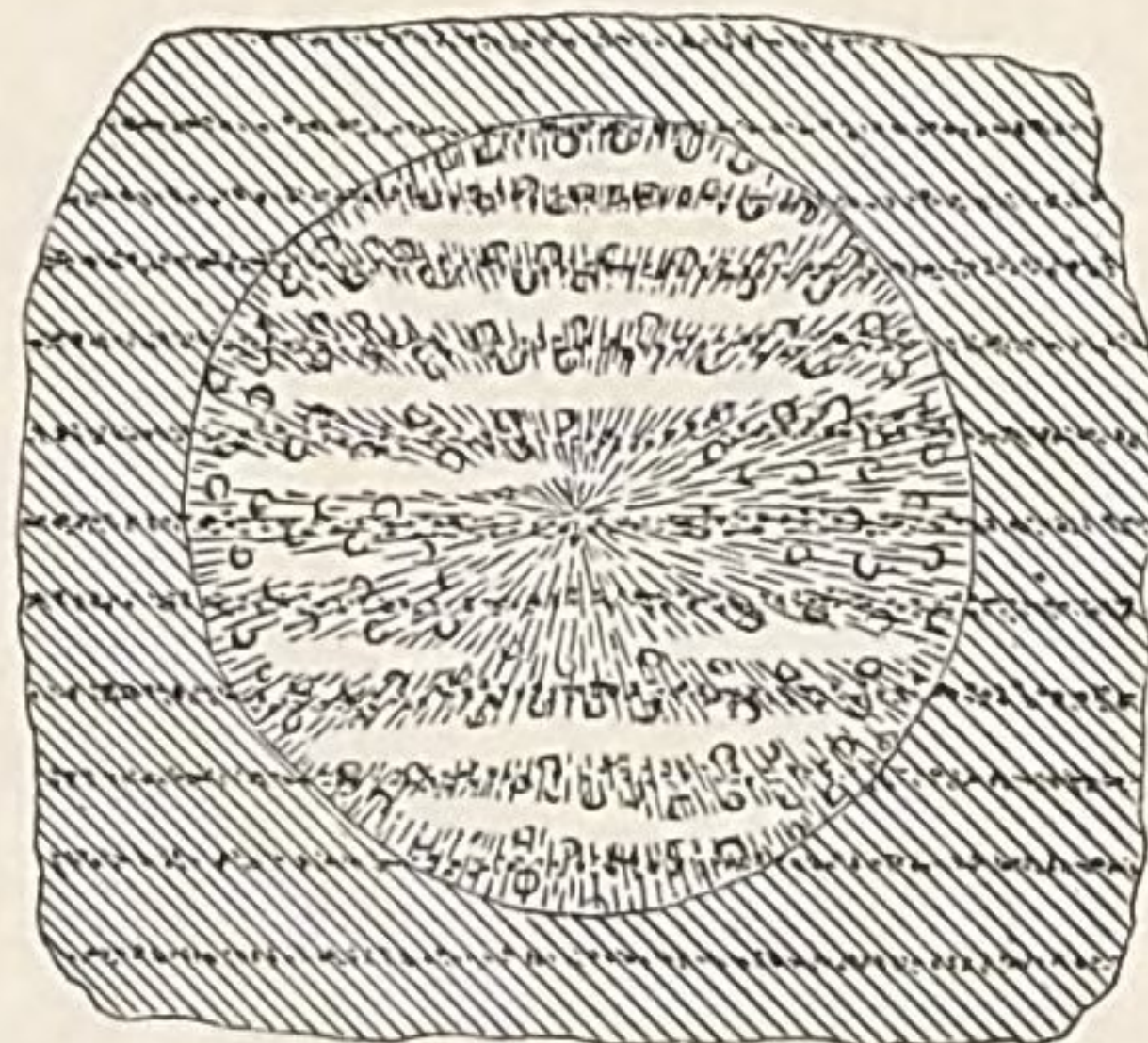
From the foregoing it is evident that lithophysæ differ from spherulites neither in outward form nor general structure, but in the nature and continuity of the material composing them. At first sight it would appear as though the substance of the spherulites had been attacked by some corrosive agent which had partially reduced it and deposited in the resulting cavities the crystals already alluded to. How far this may have been the case will appear in the sequel.

MINERALS COMPOSING LITHOPHYSÆ.

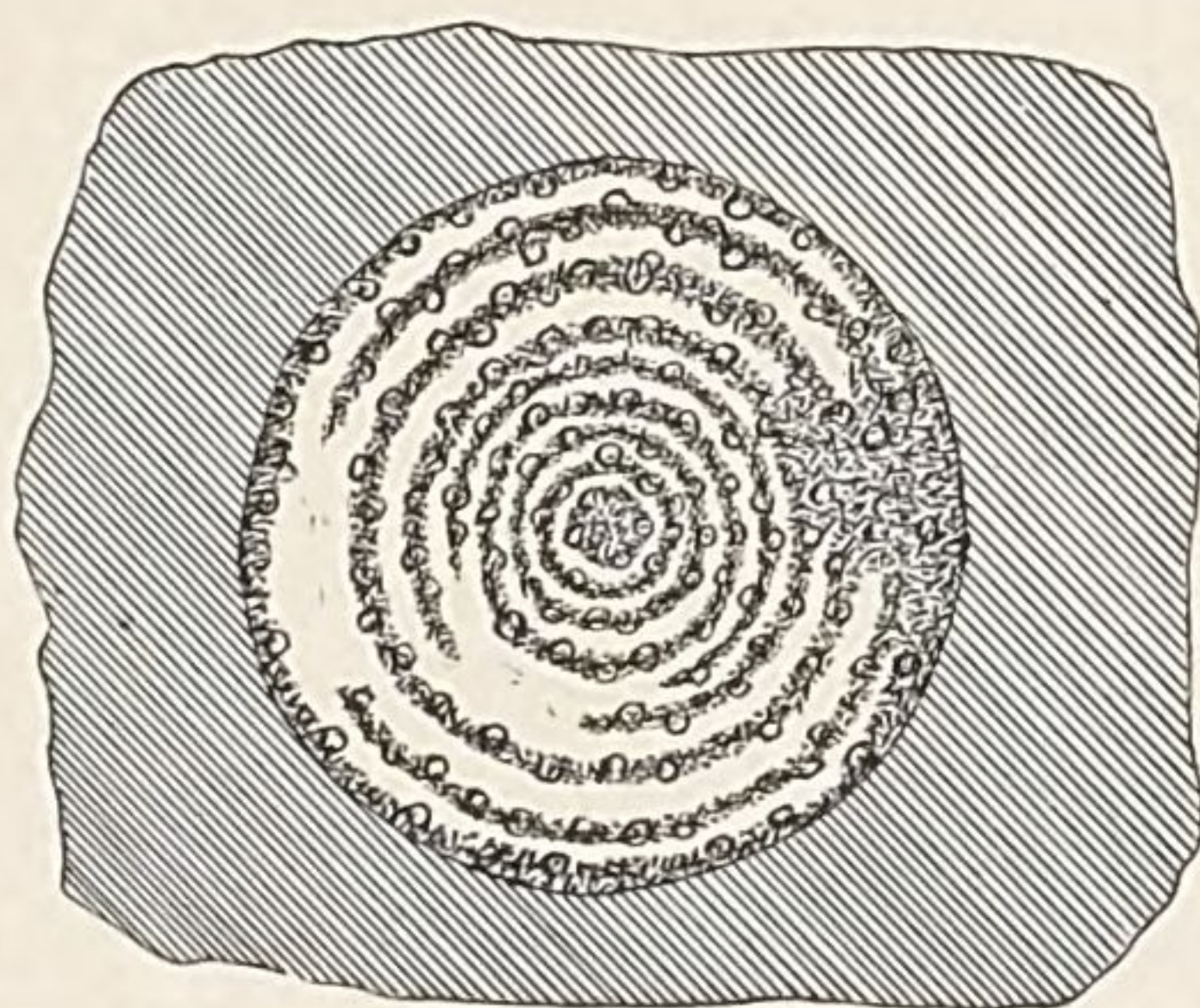
The minerals which coat the walls of the lithophysæ and make up the material which is found in the perfectly fresh ones are quartz, tridymite, feldspar, fayalite, and magnetite. The size of the crystals bears a direct relation to the size of the cavity in which they have been developed when the lithophysa is isolated in a glassy matrix. The crystals are very minute in small lithophysæ and larger in the large ones, the character of the minerals remaining the same. Where several lithophysæ are connected or where a system of cavities traverses the rock a separation of the minerals takes place, certain varieties being deposited in particular localities, producing larger crystals whose size bears no relation to that of the cavity in which they occur.



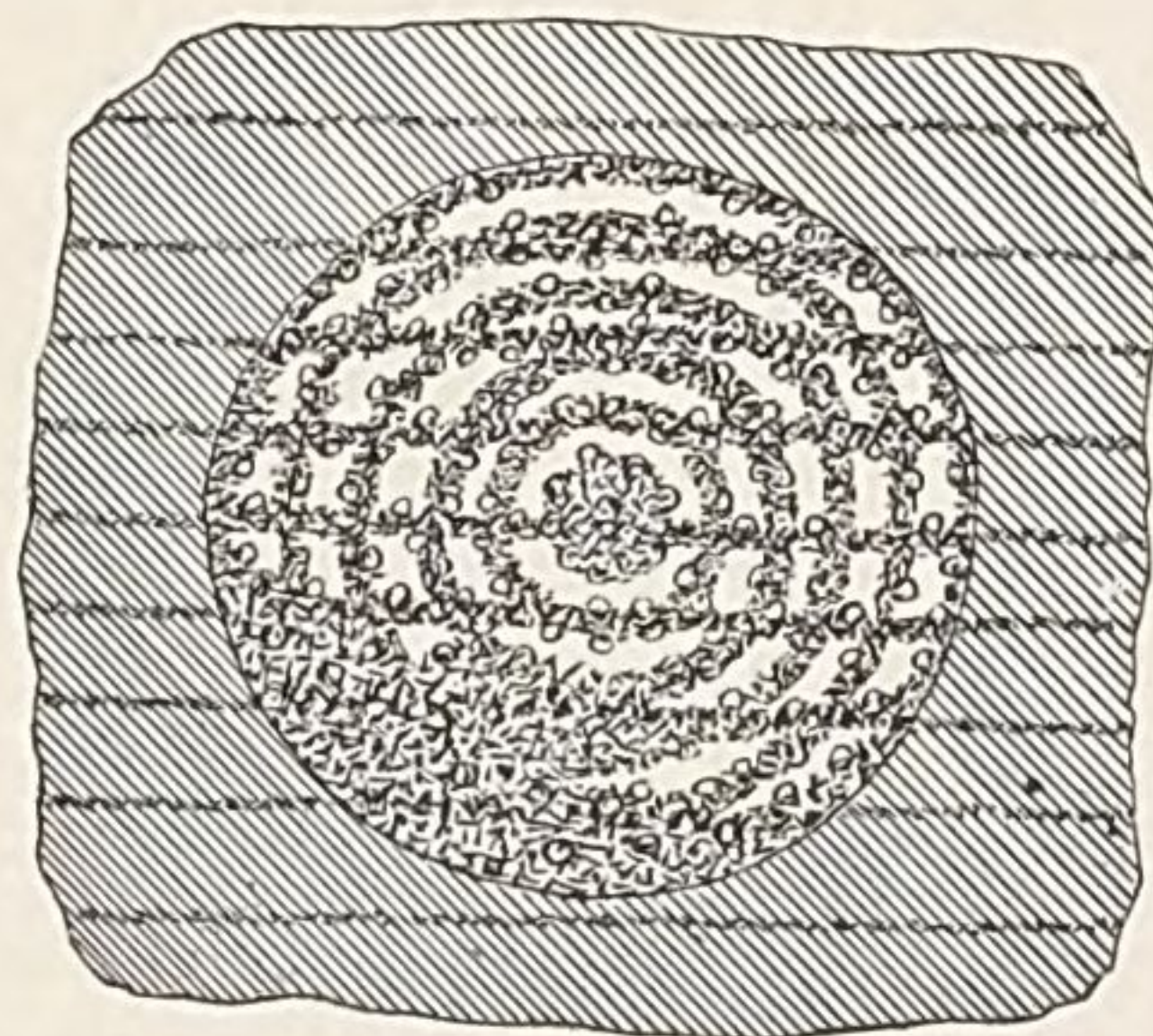
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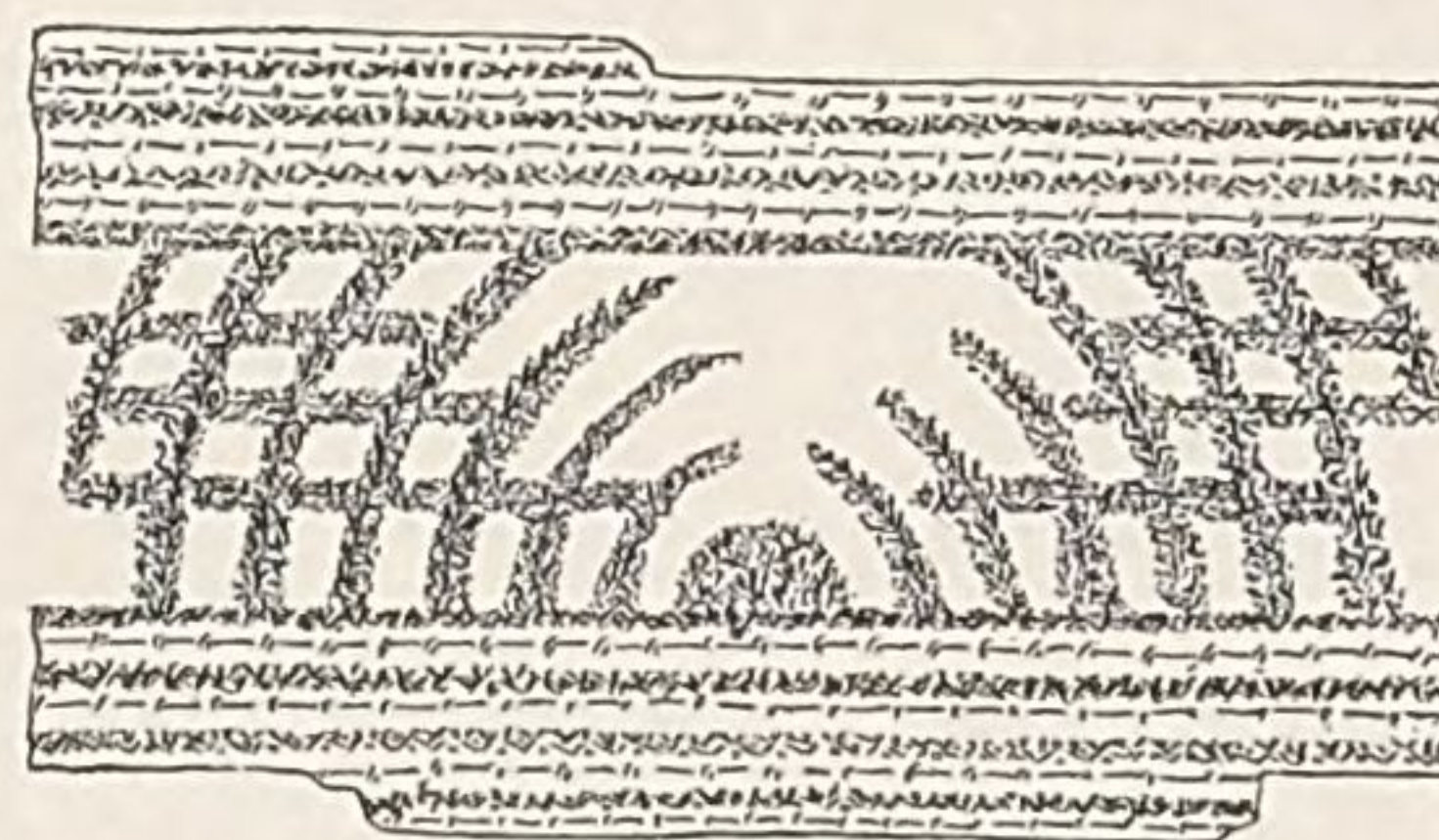
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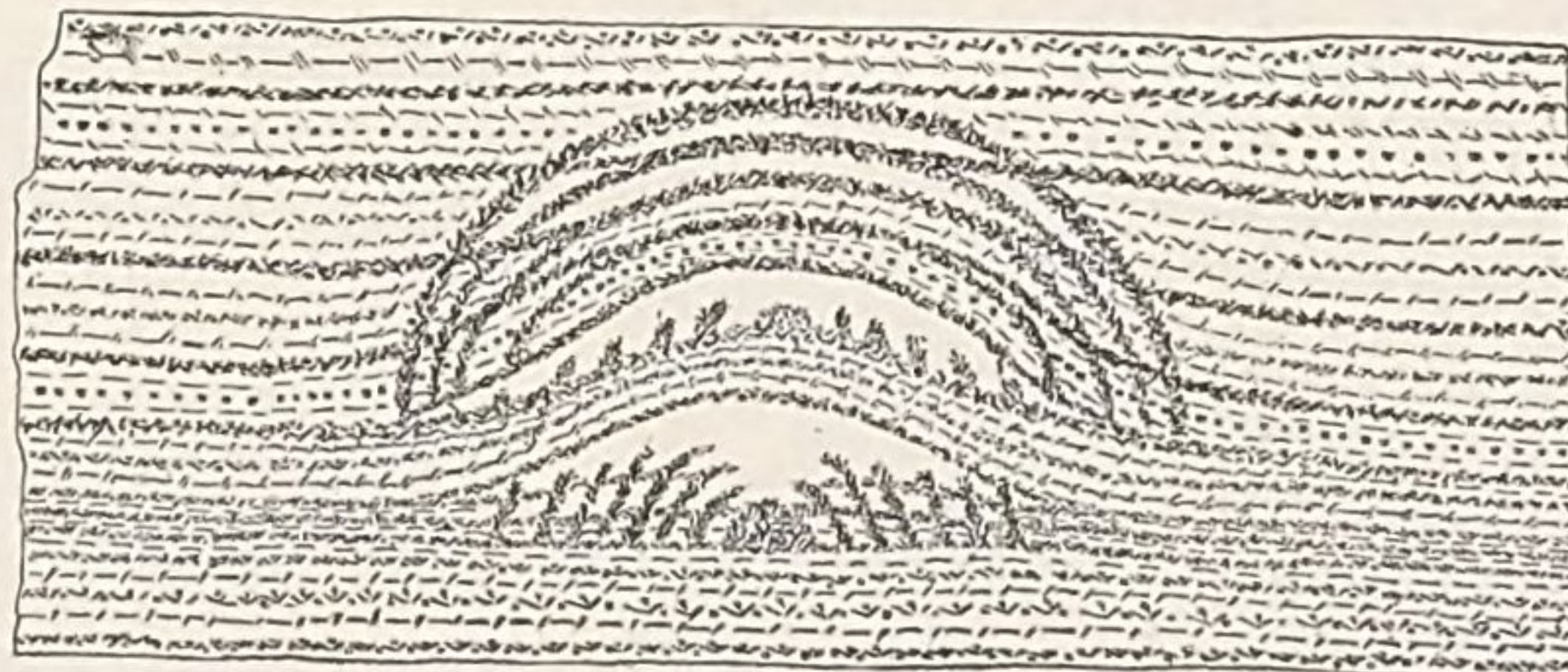
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Quartz is in prismatic crystals characteristic of this mineral when freely developed in cavities. The crystals are often doubly terminated with two sets of rhombohedrons, the ordinary set, $\pm R$, and a steeper one, and occasionally a scalenohedron. The prism faces are strongly striated transversely. The substance of the quartz is very pure and transparent, with numerous gas cavities inclosed in it.

Tridymite, the second form of silica found in lithophysæ, is in delicate, six-sided plates. The larger crystals, which may be recognized by the unaided eye, are 0.5^{mm} (one-fiftieth of an inch) broad and have rather stout, tabular forms with a very simple combination of faces. They are easily confounded with the feldspars, on account of their form as well as of their substance, which is transparent and colorless, with scattered gas inclusions. Between crossed nicols they show the optical anomalies characteristic of tridymite. The crystals are frequently single or grouped in clusters, which latter, when composed of microscopic individuals, appear as minute pellets. The tridymite is deposited along with prismatic quartz in varying proportions, sometimes one occurring to the exclusion of the other.

Two forms of *feldspar* have so far been recognized. One is in almost microscopic crystals, which make up the coarser fibers in the lithophysæ. They are short and stout, with the form characteristic of adular, that is, in rhombic prisms bounded by the unit prism faces and terminated by a striated, compound face formed of the basal plane and an orthodome. These short prisms are attached to one another end to end, making crooked and forking branches of feldspar.

Another form is found in the lithophysæ of the lithoidal rock and the cavities connected with them, where the largest crystals

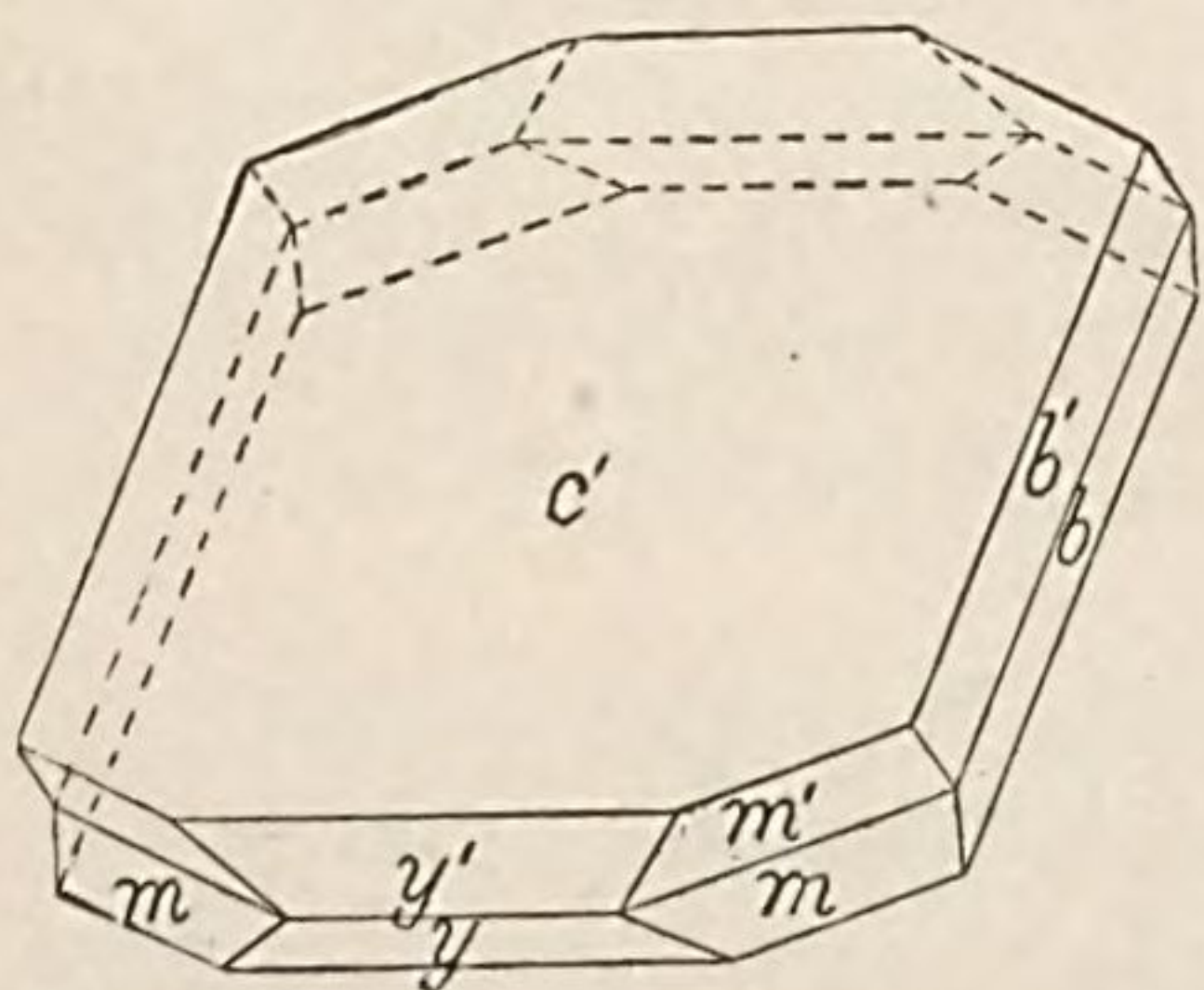


FIG. 52. Twinned crystal of soda orthoclase.

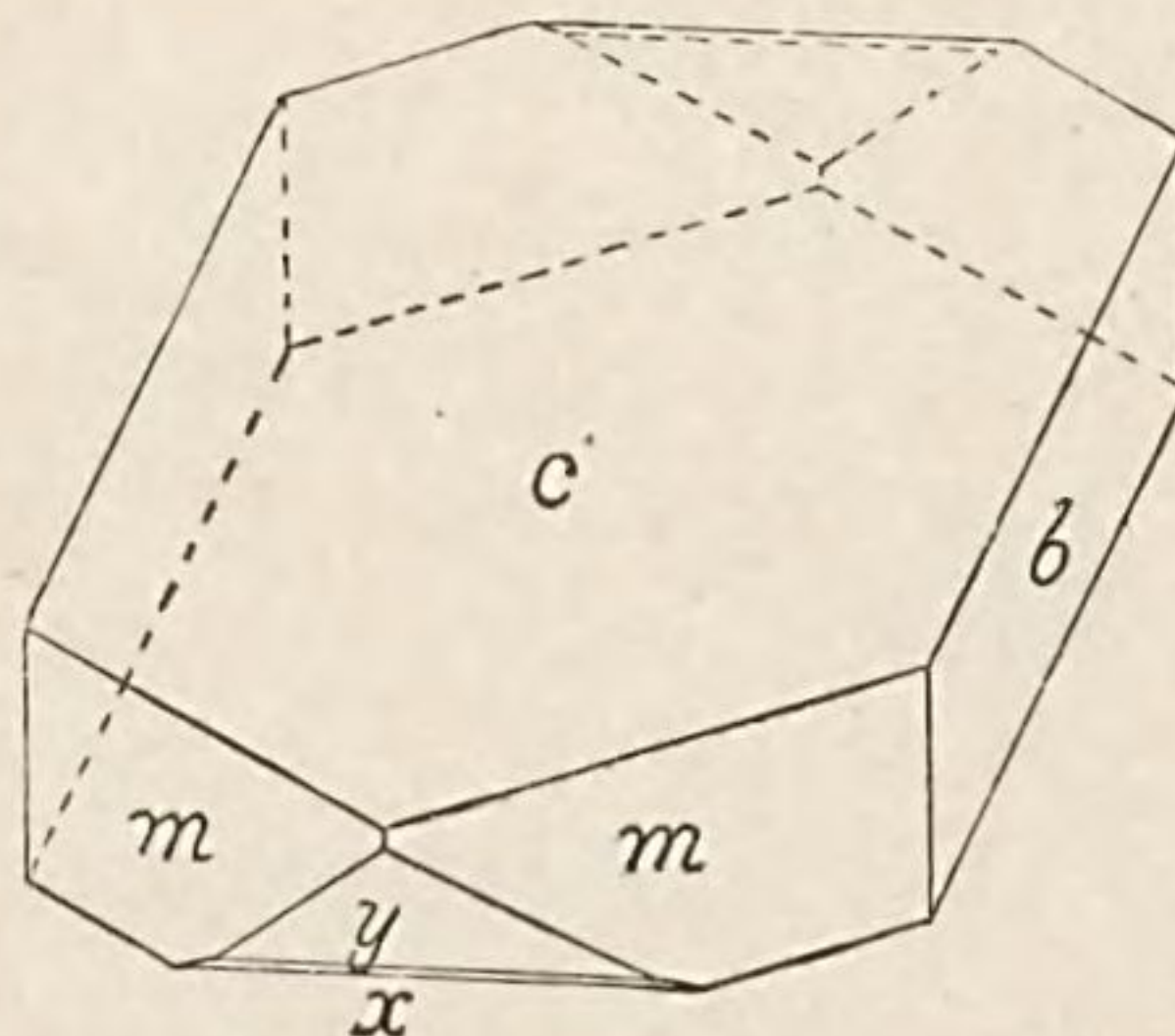


FIG. 51. Crystal of soda orthoclase.

occur. They are thin, tabular crystals about 1^{mm} broad, flattened in the plane of the base, and bounded by the clinopinacoid, prism, and two orthodomes. Such a development of the basal plane is quite uncommon for orthoclase, of which species these feldspars prove to be a somewhat doubtful variety. Mr. S. L. Penfield, of the Sheffield Scientific School, has measured and figured the crystals, besides making a chemical analysis of them.

The simple and usual form is represented in Fig. 51, though many of the crystals are much thinner than this. They are frequently twinned according to the Manebacher law, as in Fig. 52, and very rarely according to the Baveno law.

The axial ratio of the crystals was found from the following measurements:

$$\begin{aligned} m \wedge m, 110 \wedge 110, 60^\circ 12' \\ c \wedge m, 001 \wedge 110, 67^\circ 27' 30'' \\ c \wedge y, 001 \wedge \bar{2}01, 80^\circ 58' 30'' \\ \text{giving } a : b : c = 0.6466 : 1 : 0.5522 \\ \text{and } \beta = 63^\circ 41' 50'' \end{aligned}$$

Additional angles measured and calculated were as follows:

	Measured.	Calculated.
$c \wedge x, 001 \wedge \bar{1}01$	$50^\circ 53'$	$50^\circ 55' 30''$
$c \wedge b, 001 \wedge 010$	$\left\{ \begin{array}{l} 90^\circ \\ 90^\circ 5' \end{array} \right.$	90°

Angle $c \wedge b$ could not be measured very accurately, owing to poor reflections from the faces. The reflections from x also were very faint. These measurements show that the crystals belong to the monoclinic system, and their habit is that of orthoclase feldspar, but their optical character is not that of a monosymmetric mineral. The thin, tabular crystals furnish plates parallel to the basal plane and readily permit of optical investigation in this position, which is a fundamental one for a monosymmetric crystal. The edge made by the base and clinopinacoid is sharply defined, and the edge between the orthodome and base is seen to be exactly at right angles to it, as closely as can be measured by the cross-wires of the microscope. But between crossed nicols these basal plates do not extinguish the light parallel to the trace of the clinopinacoid, as they should do if the crystals were monosymmetric, and in convergent polarized light it is found that the plane of the optic axes makes a small angle with the clinopinacoid, which in the first eleven feldspars examined ranged from 1° to 4° . In fifteen more feldspars examined with the wide-angle, immersion, Bertrand lens of Nachet et Fils, the inclination ranged from $1^\circ 30'$ to $5^\circ 12'$, in no case being 0° .

The inclination of the bisectrix to the edge $c b$ measured on the clinopinacoidal face of cleavage pieces varied from $+6^\circ$ to $+10^\circ$.

Optically the crystals are asymmetric and approach the recently described anorthoclase of Klein¹ and Förstner.² It is to be hoped that better material may be found which will furnish larger crystals for a thorough determination of the optical properties of these abnormal feldspars.

The substance of the feldspars is perfectly transparent, with minute gas inclusions. The crystals exhibit a brilliant, blue opalescence that appears to be reflected from planes of microscopic parting parallel to an orthodome, indicated by delicate lines, which, on the basal

¹ Ueber die Feldspath im Basalt von Hohem Hagen etc.: Göttinger Nachrichten, 1878, No. 14; Neues Jahrbuch für Mineral., 1879, p. 518.

² Ueber die Feldspäthe von Pantelleria: Zeitschr. für Kryst., 1883, vol. 8, p. 125.

plane, lie parallel to the axis *b*, and, on the clinopinacoid, make an angle of about $71^{\circ} 42'$ with the axis *a*. This corresponds closely to the observations of Mr. Whitman Cross¹ on the sanidines in the rhyolite of Chalk Mountain, Colorado, and still further confirms the deductions of E. Reusch,² who ascribed the iridescent colors noticed in many labradorites and other feldspars to the effect of thin plates due to delicate parting in certain directions through the mineral.

The chemical composition of these feldspars is shown by the following analysis made on less than a gram of material, which was obtained by means of Thoulet's solution of iodide of potassium and iodide of mercury — a solution which may be prepared with a specific gravity of about 3, when it will float many of the rock-making minerals, the heavier ones falling to the bottom. By gradually diluting the solution with water its density may be lowered to that of the suspended minerals, which one by one will settle to the bottom, as the specific gravity of each is passed. In this way the feldspars were separated from portions of the rock mixed with them and fell between the specific gravities of 2.589 and 2.541.

Partial analysis, I, was made on 0.6002 gram, and, II, on 0.3581 gram.

	I.	II.	Mean.	Ratio.
Silica, SiO ₂	a67.78	67.29	67.53	1.125
Alumina, Al ₂ O ₃	17.85	18.13	17.99	.174
Ferric oxide, Fe ₂ O ₃	0.54	0.66	0.60	
Lime, CaO	b0.09		0.09	.002
Soda, Na ₂ O	5.08	.....	5.08	.082
Potash, K ₂ O	8.36	.....	8.36	.088
Ign.		0.30	0.30	
			99.95	

a Determined by difference.

b Determined by uniting both portions.

The ferric oxide was derived from a little yellow oxide of iron which coated some of the crystals and may be omitted in discussing the analysis.

The ratio

$$\begin{array}{l} \text{SiO}_2 : \text{Al}_2\text{O}_3 : \text{R}_2\text{O} \\ 1.125 : .174 : .172 \\ 6.54 : 1.01 : 1.00 \end{array}$$

indicates a slight excess of silica, probably due to a small amount of quartz or tridymite which adhered to the feldspar crystals. Eliminating this excess of silica, which, when calculated to bring the ratio

¹ Contributions to the Mineralogy of the Rocky Mountains, Whitman Cross and W. F. Hillebrand: Bull. U. S. Geol. Survey No. 20, 1885, p. 75.

² Ueber das Schillern gewisser Krystalle: Poggendorff, Annalen, vol. 116, p. 392; *ibid.*, vol. 118, p. 256; *ibid.*, vol. 120, p. 95.

of $\text{SiO}_2 : \text{Al}_2\text{O}_3 : \text{R}_2\text{O} = 6 : 1 : 1$, would be 5.25 per cent., the analysis becomes

Free silica, SiO_2	5.25		
Silica, $\text{SiO}_2\frac{1}{2}$	62.28	1.038	6
Alumina, Al_2O_3	17.99	.174	1
Ferric oxide, Fe_2O_3	0.60		
Lime, CaO	0.09	.172	1
Soda, Na_2O	5.08		
Potash, K_2O	8.36		
Ignition	0.30		
	99.95		

which will reduce to

Silica, SiO ₂	66.40		1.107	6
Alumina, Al ₂ O ₃	19.18		.186	1
Lime, CaO	0.10	.002	.183	1
Soda, Na ₂ O	5.41	.087		
Potash, K ₂ O	8.91	.094		
	100.00			

From the ratio of the alkalis in this analysis, the feldspar may be considered as an isomorphic mixture of orthoclase and albite in nearly equal proportions; its formula will then be Or_1Ab_1 . It is the middle member of the orthoclase-albite series, with apparently the crystallographic characters of orthoclase, though somewhat exceptionally developed, but with the optical characters of a triclinic feldspar—an anomalous combination of characters which requires further investigation.

Fayalite is in small, tabular crystals scattered through the lithophysæ, usually projecting from the walls of the cavities, its crystals being larger than those of the associated minerals. In most instances they appear as opaque, black crystals about 2^{mm} and less in length; their form is flattened, or tabular, with orthorhombic symmetry. They frequently have a metallic luster, occasionally with brilliant, iridescent colors, mostly reds. Examination shows that these crystals are coated with ferric oxide, the interior of the crystals being transparent and of a light-yellow color. Perfectly fresh, unaltered crystals are found in the small lithophysæ isolated in the obsidian, where they have been preserved from the action of the atmosphere. The best crystals of this sort were found in compact, black obsidian, about half a mile north of Lake of the Woods, near the southern end of this obsidian sheet. They are in thin, square or rectangular plates, of a light honey-yellow color, perfectly transparent and free from inclusions of other minerals, but occasionally containing gas cavities. They show very slight pleochroism, pale greenish yellow parallel to the b axis and golden yellow parallel to the c axis. The cleavage parallel to the brachypinacoid is good, but a second at right angles to the first is less distinct and is probably in the plane of the macropinacoid, as in olivine.

Mr. S. L. Penfield has kindly determined and figured the crystallographic forms presented by the rectangular, tabular crystals from the locality north of the Lake of the Woods and the more elongated and pointed crystals from Obsidian Cliff. The measurements were made on a thin, tabular crystal 0.1^{mm} thick and 0.8^{mm} broad, which was broken across the prismatic zone. The observed forms were *a* (100, $i\bar{i}$), *b* (010, $i\bar{i}$), *s* (120, $i\bar{2}$), *e* (111, 1), *d* (101, $1\bar{1}$), *k* (021, $2\bar{1}$). Arrangement of planes is quite constant, as in Fig. 53. For fundamental angles the best two reflections were chosen:

$$\begin{aligned} a \wedge s, 100 \wedge 120 &= 42^\circ 31' \\ d \wedge d, 101 \wedge \bar{1}01 &= 103^\circ 17' \\ \text{giving } \bar{a} : \bar{b} : \bar{c} &= 0.4584 : 1 : 0.5791 \end{aligned}$$

The angles measured and calculated were:

		Measured.	Calculated.
<i>a</i> $\wedge$ <i>b</i>	100 $\wedge$ 010	90°	90°
<i>s</i> $\wedge$ <i>s</i>	120 $\wedge$ 120	95° 8'	94° 58'
<i>a</i> $\wedge$ <i>d</i>	100 $\wedge$ 101	38° 20'	38° 22'
<i>d</i> $\wedge$ <i>e</i>	101 $\wedge$ 111	19° 52'	19° 46'
<i>e</i> $\wedge$ <i>e</i>	111 $\wedge$ $\bar{1}11$	95° 5'	95° 6'
<i>a</i> $\wedge$ <i>e</i>	100 $\wedge$ 111	42° 25'	42° 27'
<i>b</i> $\wedge$ <i>k</i>	010 $\wedge$ 021	40° 45'	40° 49'

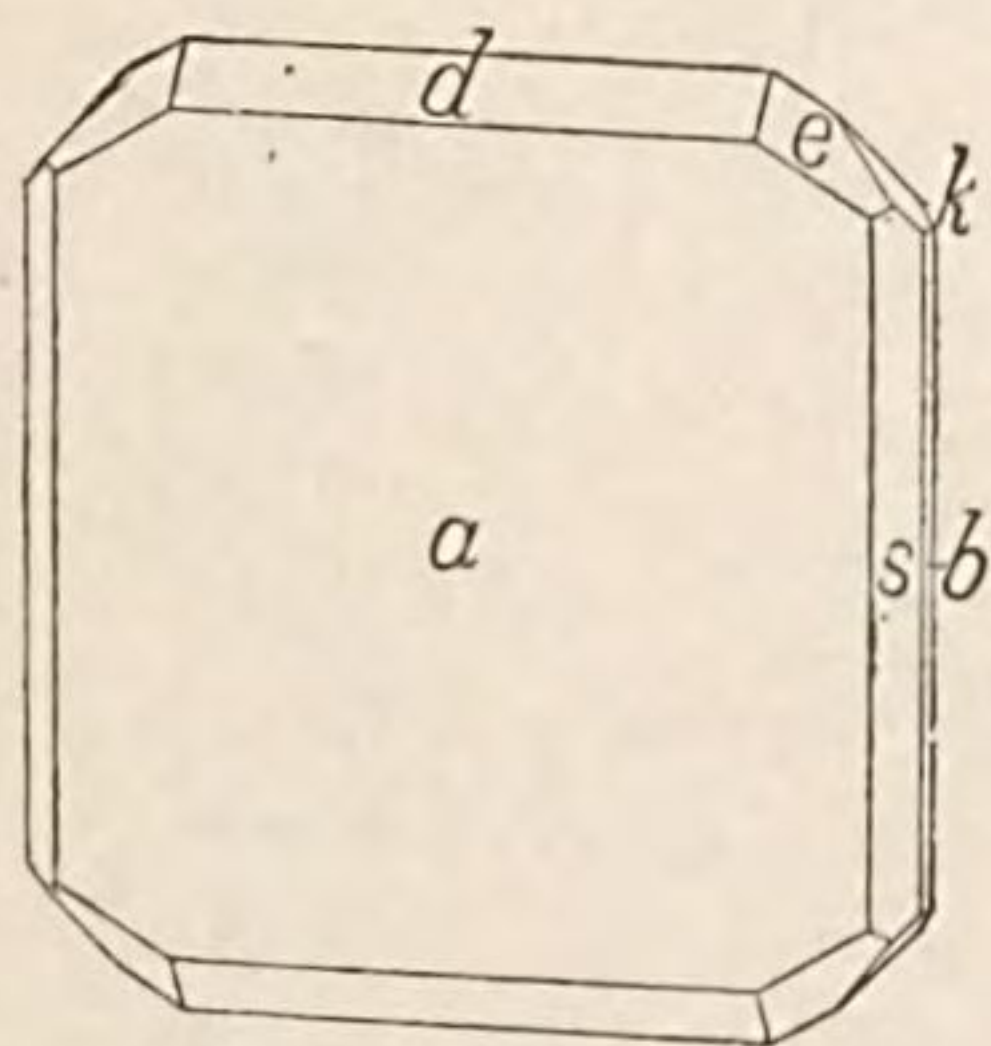


FIG. 53. Crystal of fayalite.

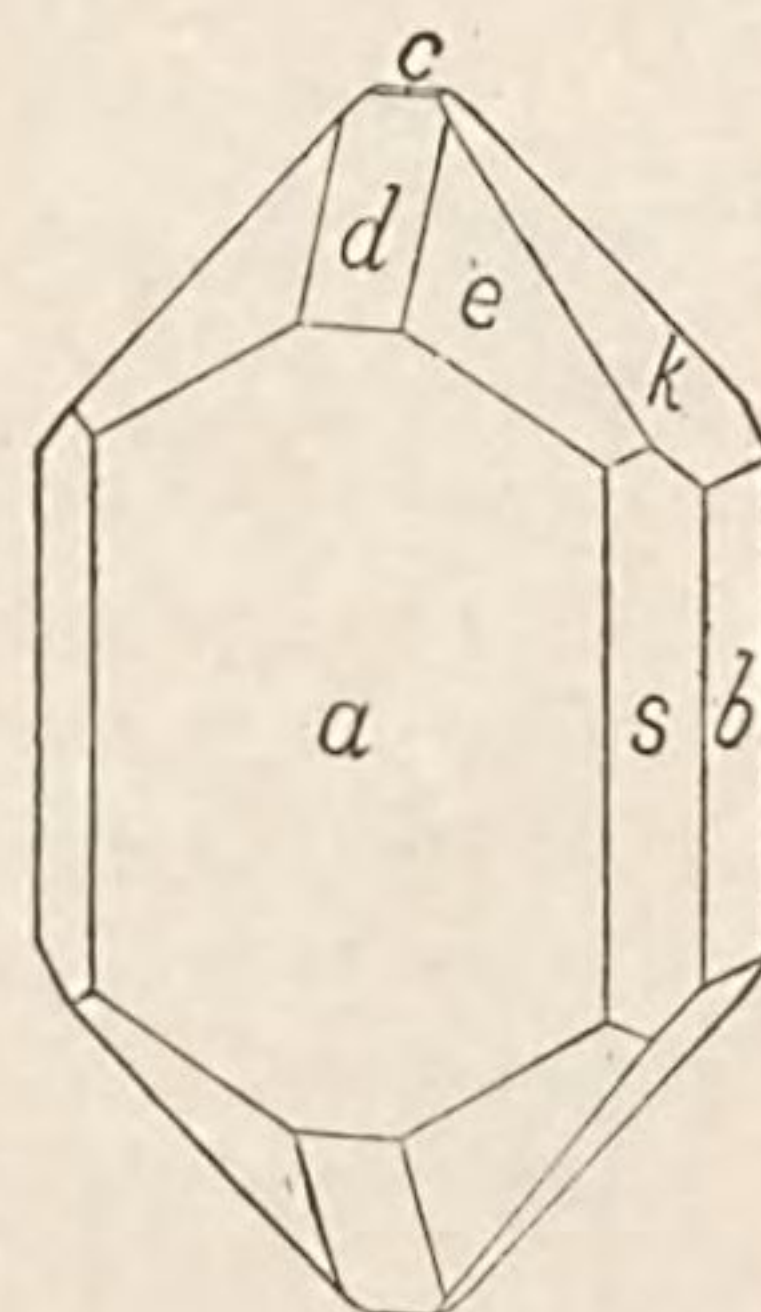


FIG. 54. Crystal of fayalite.

The plane of the optic axes is parallel to the base, one of the bisectrices being normal to the macropinacoid, as shown by a polarizing microscope. Owing to the minuteness of the crystal examined, the divergence of the optic axes was not determined.

The opaque crystals from Obsidian Cliff show the same forms, with the additional basal plane, *c*, but are mostly developed as in Fig. 54. With the exception of the macropinacoid, the faces were too dull to give good reflections and the forms were identified by approximate measurements only.

This mineral is the same as that described in 1827 by Gustav Rose,¹ who measured the small crystals found in the lithophysæ in

¹Ueber den sogenannten krystallisirten Obsidian: Poggendorff, Annalen, vol. 10, 1827, pp. 323-326.

obsidian from Cerro de las Navajas, Mexico, which von Humboldt had collected.

“The crystals,” he says, “are very small, the largest half a line long and broad, and very thin, of a greenish and reddish-yellow color, transparent, but with a strong, vitreous luster.” The forms of the crystals figured by him are exactly the same as those found at Obsidian Cliff, and the angles measured are almost identical. They are as follows:

By G. Rose.		Complementary angles.	By S. L. Penfield.
$M \wedge d$	141° 37' and 38'	38° 23' and 22'	38° 20'
$k \wedge k$	80° 58' and 81° 20'		
$d \wedge e$	160° 8' and 20'	19° 52' and 40'	19° 52'
$M \wedge s$	137° 17' and 34'	42° 43' and 26'	42° 31'

From the similarity in crystallographic form and in manner of occurrence, it is probable that the crystals which Rose determined as olivine belong to the purely ferruginous variety, fayalite.

A chemical analysis of the coated crystals from Obsidian Cliff was made by Prof. F. A. Gooch, at that time in the chemical laboratory of the U. S. Geological Survey. All the material available was 0.24 gram.

Under the microscope the crystals were seen to carry a small amount of adhering quartz and to be coated with iron oxide. They were readily decomposed in hot hydrochloric acid with the separation of silica and yielded the following results:

Silica, SiO ₂	25.61
Alumina, Al ₂ O ₃	Trace
Ferric oxide, Fe ₂ O ₃	14.92
Ferrous oxide, FeO	51.75
Magnesia, MgO	1.66
Lime, CaO	None
Ignition	None
Insoluble silica	7.02
	100.96

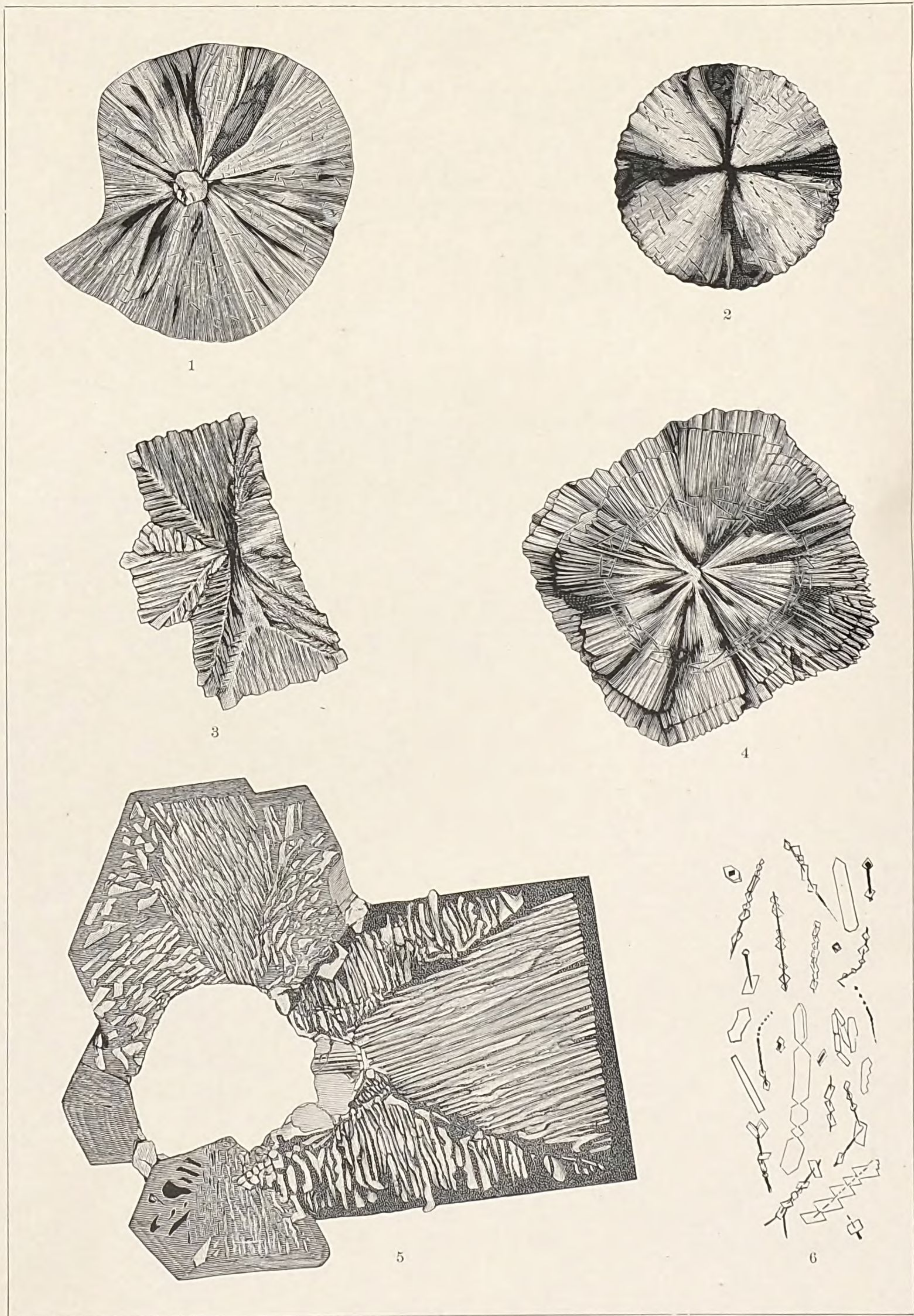
Considering the ferric oxide as the opaque coating of alteration and the insoluble silica as the adhering quartz, the composition of the unaltered mineral will be:

			Oxygen ratio.	
Silica, SiO ₂	25.61	32.41	17.275	1.12
Ferrous oxide, FeO	51.75	65.49	14.539	1.00
Magnesia, MgO	1.66	2.10	.840	
	79.02	100.00		

which is essentially the composition of the unisilicate fayalite.

In the case of the unaltered crystals from near Lake of the Woods, a very careful qualitative test by Mr. Penfield showed that these crystals were an iron silicate containing no magnesia.

The magnetite in the lithophysæ is in microscopic grains which under the microscope appear to be octahedral crystals.



SECTIONS OF SPHERULITES AND GRANOPHYRE GROUPS.

MICROSCOPICAL CHARACTERS.

Having familiarized ourselves with the general outward appearance of the rock forming Obsidian Cliff, let us look deeper into the subject and by means of the microscope penetrate to the very heart of the matter. To this end thin sections of the rock were prepared by grinding one side of small fragments about the size of a 25-cent silver piece and polishing it smooth, cementing this to glass by means of heated Canada balsam, and then grinding away the other side of the rock until it became thin enough to be transparent, when by very skillful polishing the section was reduced to a thinness almost imaginary, 0.001 of an inch and thinner. With such sections magnifying powers as high as 1,500 diameters may be employed if necessary, permitting very little to escape notice. For most purposes, however, a power of 100 diameters is all sufficient.

TRICHITES AND MICROLITES.

The black obsidian in thin section becomes perfectly transparent and of a gray color. Under the microscope it is seen to be a colorless glass crowded with minute, transparent, pale-green crystals and short, black, hair-like bodies called trichites. The crystals are in thin rhombic tablets or irregular grains, 0.005^{mm} ($\frac{1}{5000}$ inch) in diameter, either scattered about or strung on the short, opaque threads like conserved cherries on a straw (Pl. XV, Fig. 6). The larger of these transparent microlites, or microscopic crystals, prove to be a variety of augite, which only appears in microscopic forms in this rock. The trichites are about 0.0008^{mm} (0.000032 inch) wide and may be traced through different gradations to grains of magnetite, which in larger form are recognized in the glass intimately associated with the augite, usually inclosed in a grain or crystal of the latter mineral. These trichites give the obsidian its black color. Such microlites and trichites are found in nearly all volcanic glasses and differ in shape and character according to the condition and composition of the lavas in which they occur. They are rudimentary crystals of minerals which develop in rapidly solidifying glasses, where a larger and more perfect crystallization is hindered by the viscosity of the glass.

The strings of microlites and trichites often have a distinctly parallel arrangement and are in layers of greater or less abundance, which mark the planes of flow within the glass.

Occasionally the trichites are in curved groups, radiating from a central grain and looking like the downy seed of a thistle. One variety of red obsidian derives its color from bright-red trichites and grains, due probably to the higher oxidation of the iron. Most of the brownish-red varieties are composed of colorless glass through which run orange and yellow, microscopic streaks and ribbons in the greatest complex of contortions and streams (Pl. XVI, Fig. 1), often

producing very grotesque and curious shapes, among which one recognizes the forms of flowers, toad-stools, sea-anemones, jelly-fish, spearheads, and the like, a list only limited by the size of the thin section and the imagination of the observer.

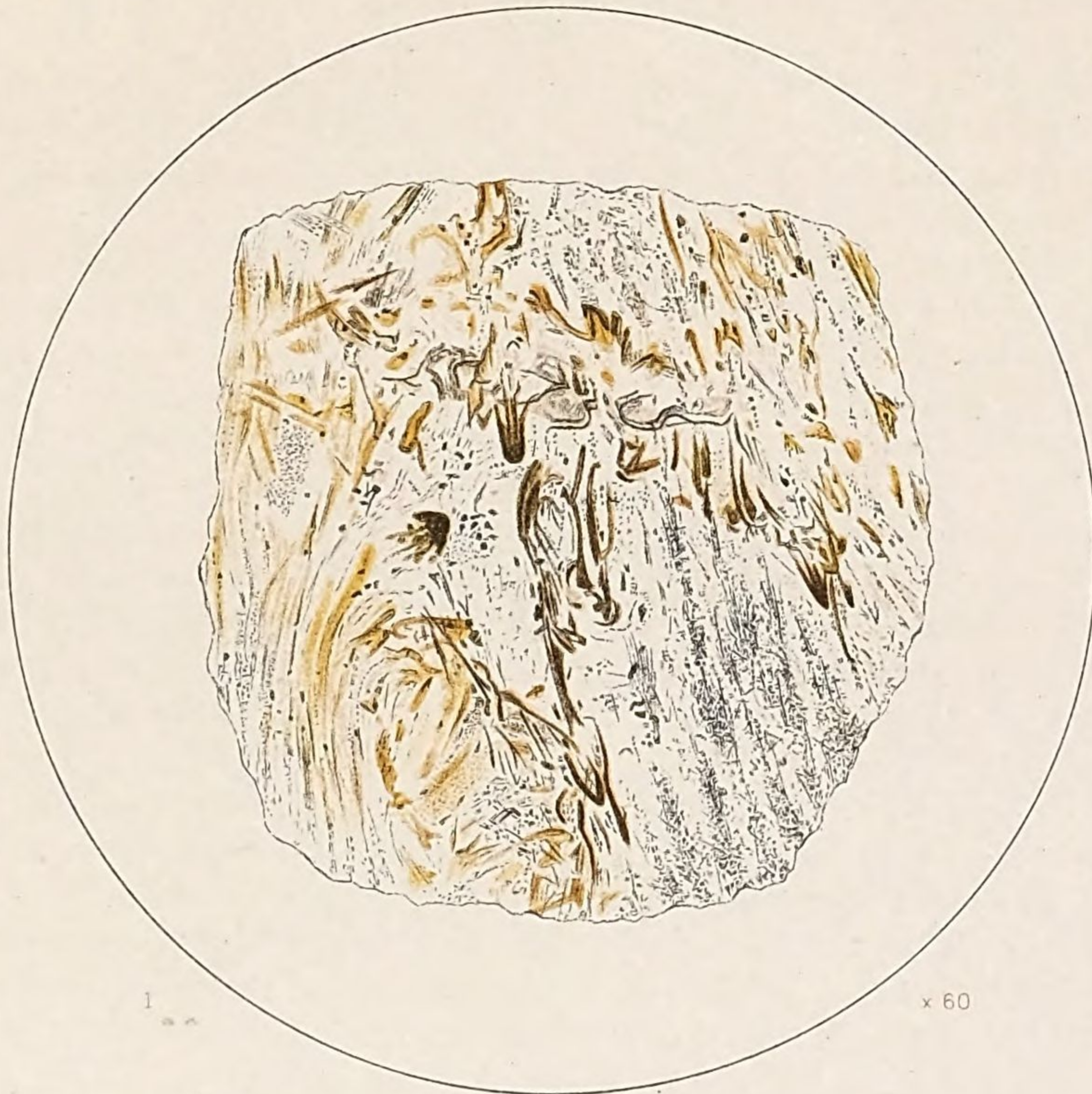
These colored bands, when highly magnified, appear to be composed of the minutest yellow or orange granules. In places there is a shading through brown into black, which is accompanied by a shrinkage of the bands, and in their stead is clear glass streaked with clouds and lines of opaque grains and trichites, apparently magnetite. Some of the clouds of minute grains look blue in transmitted light.

The various shades of color in the obsidian arise from the different proportions in which these yellow, orange, brown, and black particles are mingled. In some the colored streaks are in broad, thin bands, either straight or twisted, according to the last movements of the viscous glass. In others they are in the most delicate threads, alternating with streaks of black grains running continuously through the rock, though sometimes interrupted by streaked patches of other character or appearing as though the rock had been broken into fragments and welded together again (Pl. XVI, Fig. 2). The transition of the yellow and orange bands into black grains, the larger of which are recognizable as magnetite, indicates that the former are made up of finely divided particles of iron more highly oxidized, which is confirmed by the chemical analyses of the red and black obsidian. The iron in the red variety is almost wholly sesquioxide, while in the black obsidian there is a slight excess of protoxide over that required to form magnetite in combination with the sesquioxide.

The only other minerals crystallized out of this obsidian are a few microscopic crystals, suggesting feldspar, and the various spherulitic bodies. We shall consider the different forms of crystallization in the order of their production or growth, having already started with the first, namely, the trichites and microlites of magnetite and augite.

GRANOPHYRE GROUPS.

Following these come the microscopic crystals of what at first appears to be feldspar. They are not, however, simple feldspar, but an intergrowth of this mineral with another in groups of small crystals with the nearly rectangular outlines of feldspar, averaging 0.2^{mm} (0.008 inch) in diameter. Close inspection with a high magnifying power reveals the fact that each group is composed of several individuals of feldspar intersecting one another and that each individual has a fibrous structure in several directions through it and is granular in places. This is represented in Pl. XV, Fig. 3, where a section has been cut through two individuals, one end of one not having been developed. The fibers run nearly perpendicularly to the sides of each rectangle. The margin of what appeared to be a straight-



Y. SINCLAIR & SONS, LITH. PHILA.

RED OBSIDIAN IN THIN SECTIONS.

edged crystal section is found to be serrated with the projecting ends of minute crystals. The component minerals are too finely divided to be determined optically; all that can be observed is the general structure, that they are colorless, and that between crossed nicols they extinguish light at various angles to the direction of the fibers. They inclose trichites and microlites, and have therefore crystallized after these.

Their structure recalls that of other groups of colorless minerals noticed in rocks of similar composition which occur in the neighboring regions, namely, the rhyolites of the Great Basin of Utah and Nevada, where we find similar groups of larger size, and in a rock from Eureka, Nev., there is one large enough to allow of the optical determination of the component minerals. This is represented in Pl. XV, Fig. 5, as it appears between crossed nicols when magnified 37 diameters. It is a section through three orthoclase feldspars that have crystallized about a grain of plagioclase, part of which has fallen out in grinding. The section has been so placed between crossed nicols that one orthoclase is dark and the others are light gray. Inclosed in the feldspar substance are strips of another mineral which appear white in two feldspars, but white, gray, and black in the third. This mineral is quartz, which has formed at the same time as the feldspar and has been inclosed in its mass. It is in shreds, which are long and thin or short and irregularly shaped. Many of them are bounded by crystallographic faces, which in cross-section give triangular and polygonal figures characteristic of pegmatite. All the quartz shreds in the largest two feldspars have the same crystallographic orientation, as though they belonged to one continuous crystal, but in the smallest feldspar the quartz shreds are in three sets, with different orientations. Thus, in one instance, quartz in one position is combined with feldspar in two positions, and, in another, quartz in three positions is combined with feldspar in one. In the largest individual, while the clear margin of feldspar extinguishes light at one angle and the quartz at another, in that portion where the thin shreds of quartz alternate with those of feldspar the maximum extinction of light takes place in various positions, according to the relative thickness of the two minerals through which the light passes. Hence we find in this fibrous portion different extinctions, none of which corresponds to that of either of the component minerals.

From some cause the quartz ceased to crystallize before the feldspar, as is seen by the clear border and sharp, straight outline of the latter mineral, pierced, however, in several places by shreds of quartz which protrude from the surface. If the feldspar had stopped forming a little before the quartz the outline would have been serrated like that of the groups formed in the obsidian. We have, then, strong evidence that these microscopic groups are composed of feldspar and

quartz intergrown in the manner so frequently observed on a larger scale in many granites, porphyries, and rhyolites.

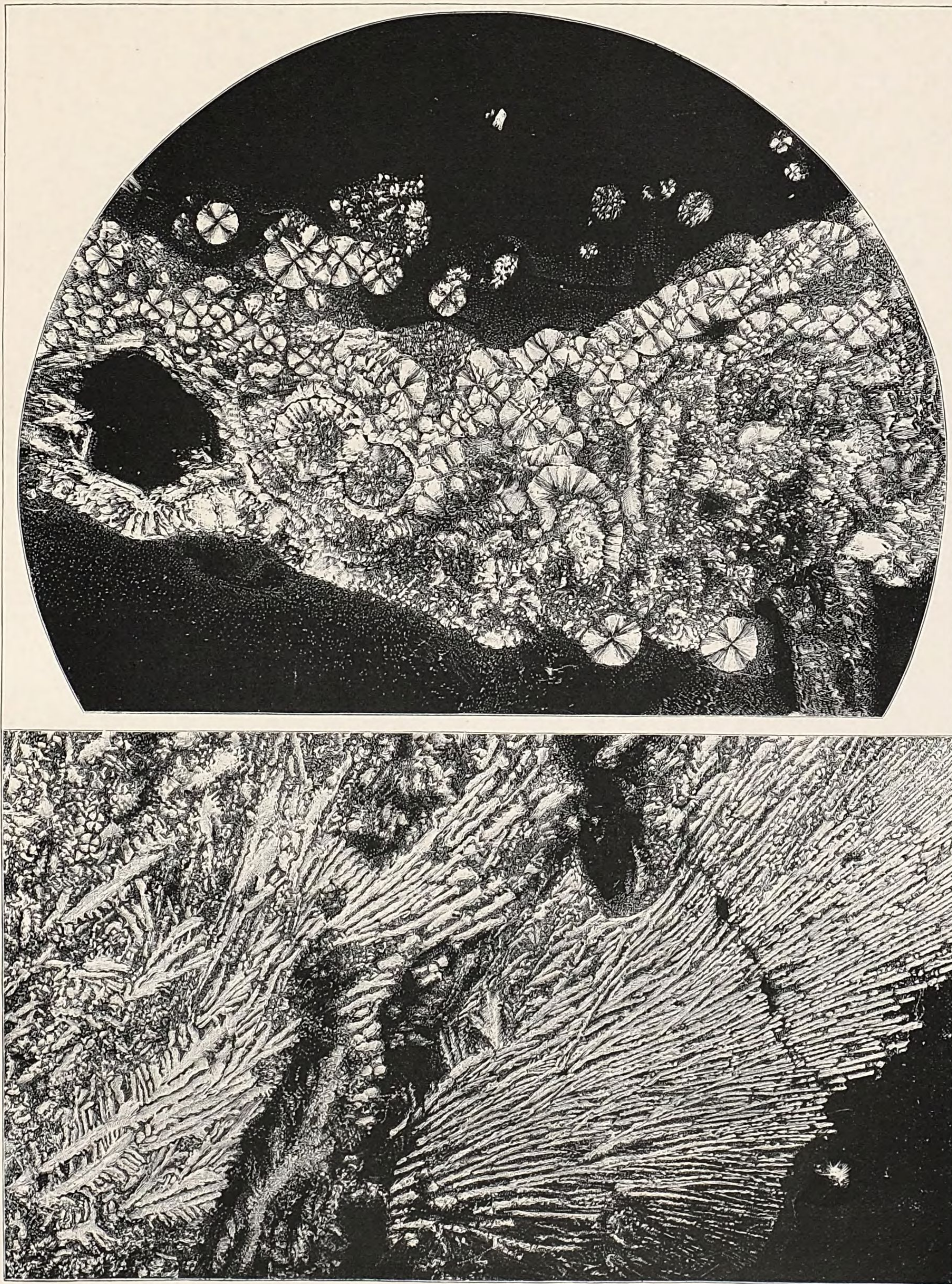
From the simple intersection of two feldspars the groups grow more complex with the increasing number of feldspars, the outline in cross-section becoming oval or circular. An extreme case is represented in Pl. XV, Fig. 4; in this the feldspars wedge out toward the center, their outer ends making an almost continuous outline and the crystal form being no longer recognizable. The fibration, however, is in wedge-shaped sets and does not radiate uniformly from the center. The extinction of light between crossed nicols is quite irregular, as shown in the drawing, and, as we observed in the rock from Eureka, Nev., the orientation of the quartz may vary greatly throughout this group, being quite independent of that of the feldspar. The inclosed trichites are crowded in a ring about the center.

These microscopic pegmatoid or granophyre groups, together with the trichites and microlites, crystallized before the lava came to rest and have been more or less twisted or turned about and arranged in layers along the planes of flow.

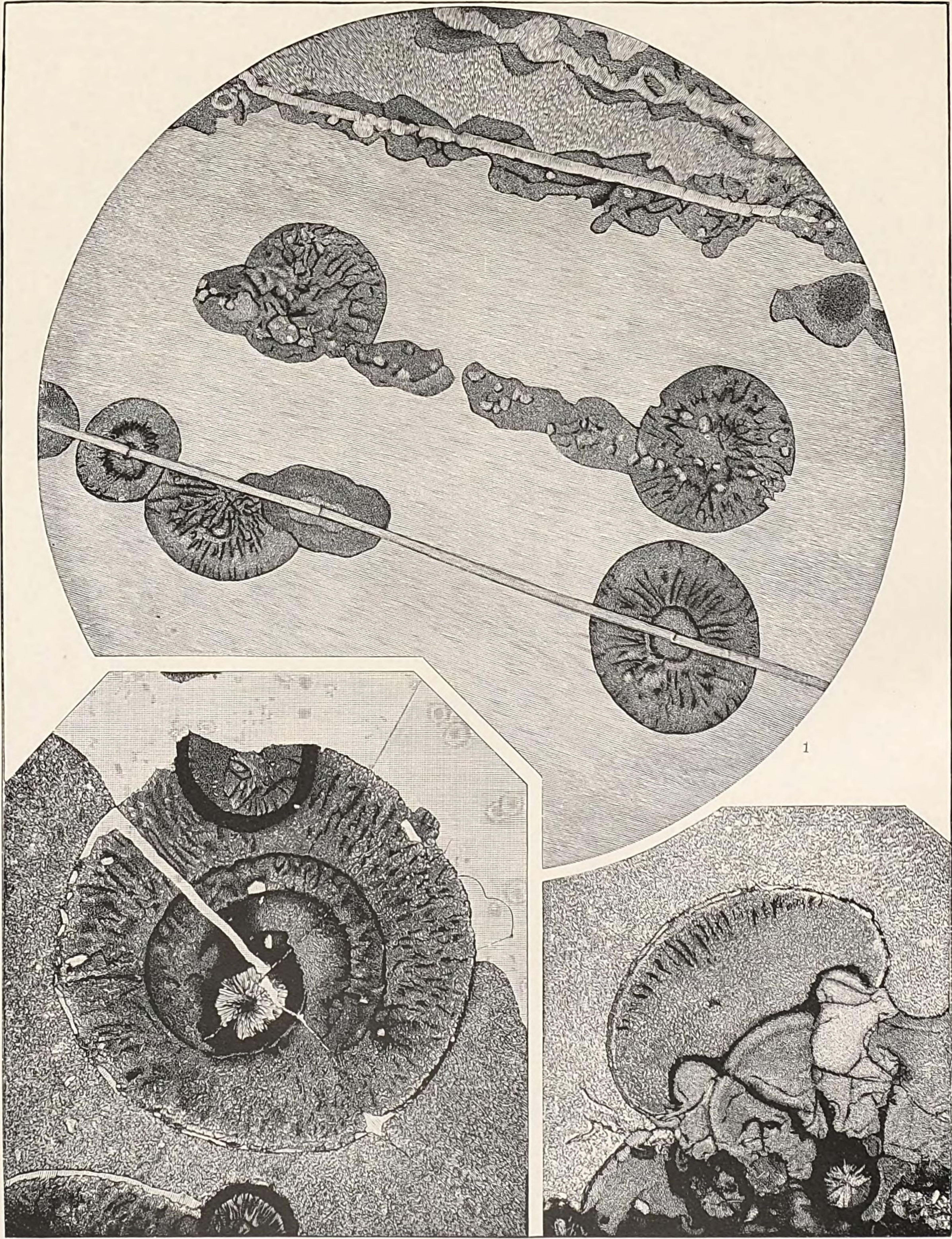
SPHERULITES.

The next order of crystallization in the obsidian is the spherulitic. The simplest and smallest as well as the first formed spherulites appear as minute, colorless spheres about 0.2 to 0.05^{mm} in diameter, scarcely noticeable in ordinary light. Highly converging light makes evident a finely fibrous structure, and between crossed nicols a more or less well defined, dark cross is observed. The arms of these crosses do not remain of constant width during the rotation of the section, but alternately contract and spread, and split into branches near their ends, as represented in Pl. XV, Fig. 2, and Pl. XVII, Fig. 1. The latter figure is from a photomicrograph taken by Mr. Clifford Richardson, of the chemical laboratory of the Agricultural Department, to whom the writer is greatly indebted for a number of beautiful photographs of rock sections taken with the aid of a solar microscope. Some of these photomicrographs are reproduced on Pls. XVII and XVIII.

A fibrous margin surrounds many of the granophyre groups; its character and length of fiber correspond to those of the smallest spherulites and from its optical behavior between crossed nicols it appears to be a continuation of the material of the inclosed kernel. The spherulites are often in rows and layers (Pl. XVII, Fig. 1) and sometimes their centers are along straight lines and so close together that they produce transparent, fibrous bands (Pl. XVIII, Fig. 1). These minute spherulites correspond to the dots observed in lines on the surface of the obsidian. After the microscopic spherulites those appearing blue in the hand specimen were formed. In thin section



SPHERULITIC STRUCTURES IN THIN SECTION.



SPHERULITES IN THIN SECTION.

they are light gray in incident light, but brown by transmitted light. They range from less than one millimeter to five and rarely ten millimeters in diameter. Under the microscope they show a finely fibrous structure, radiating from a center at which there is frequently, though not always, a granophyre group or colorless spherulite. The fibers are so delicate that many are superimposed one on another within the thin section, preventing a determination of their optical characters. Most of these larger spherulites are traversed by the streams of microlites and minute colorless spherulites which pass through them and the surrounding matrix without change of direction; but in some cases the microlites and trichites have been pushed out or crowded into radial lines (Pl. XVIII, Figs. 1 and 2). Between crossed nicols the rays of shadow seldom form a perfect cross, but are scattered and broken into many arms, some branches lying at an angle of 45° to the principal plane of the nicols. One of these spherulites is represented in Pl. XV, Fig. 1, the scattered nature of the dark rays corresponding to that exhibited by the granophyre groups (Pl. XV, Fig. 4). The fibers are in sectors and do not radiate from a single point. The smallest colorless spherulites appear to be somewhat more regular forms.

The similarity in structure and optical behavior between these spherulites and the fibrous, granophyre groups indicates a correspondence in their mineral composition which would lead us to conclude that the spherulites are composed of feldspar and quartz that have crystallized from the molten glass at one and the same time and have intergrown with each other, the fibers not necessarily being individuals of these minerals elongated in the direction of their principal crystallographic axis. This view we shall see is confirmed by their chemical composition.

The striping and banding of these spherulites in different colors arises from the crowding together of minute brown or black particles into radial or circular bands. These particles, which appear opaque by transmitted light, are often white by incident light and are probably in part gas cavities, as these are recognized in large numbers in the coarser-grained spherulites to be described. The red surface of many spherulites is produced by the higher oxidation of the trichites and opaque grains which are inclosed in them; and it is quite noticeable that the black trichites and nearly colorless microlites of the surrounding glass as they pass into the spherulites become red, as though they had encountered an oxidizing agent not active in the surrounding glass.

The forms of these radially fibrous growths are not confined to spheres, but through unequal development in different directions take the shape of hemispheres, disks, and sectors, at times spreading out like plumes (Pl. XVIII, Fig. 3), others in section resembling a fox's tail.

Porous spherulites.—The large gray and red spherulites, which have an earthy and rather porous appearance in hand specimens, are seen in thin section to be quite coarsely fibrous, which permits their structure to be clearly made out. They frequently have a dense, dark spherulite at their center and appear under the microscope to be simply the continuation of its fibers under somewhat different conditions. The fibers consist of slender needles of feldspar, often twinned and generally showing low extinction angles. The needles are not straight-edged, are frequently jointed, and branch at low angles, in some cases having short, curved needles attached like those of a pine twig. Cross-sections of the needles show them to be polygonal, but the shapes are not uniform. Between the feldspar needles are rows of tridymite scales and scattered grains of magnetite, together with abundant gas pores. The tridymite is often aggregated in spherical masses surrounding a number of feldspar needles, leaving spaces between. The presence of tridymite instead of quartz (the latter being probably the form of free silica occurring in the smaller spherulites) suggests a difference in the conditions governing the formation of the two varieties of spherulites.

Similar feldspar growths are found starting in the clear glass from a stout stem, like the limb of a tree, from which branch smaller rods that continue to fork until a radiating bunch of thin needles results, forming a partial spherulite. This is illustrated in Pl. XVII, Fig. 2. The needles are all twinned, apparently according to the Manebacher law. Their form becomes still more arborescent when the feldspar crystals are somewhat tabular and assume foliate shapes which strongly resemble oak leaves. All these structures arise from the combination of small crystals attached to one another in such a way as to produce apparently curved forms. When viewed between crossed nicols their effect is very striking and beautiful, the delicate feldspar crystals standing out in brilliant white against the black background of isotropic glass.

The light-gray bands or lithoidal layers of the rock unite two or more of the structures already described, together with coarser forms of crystallization of quartz and feldspar too numerous to describe, except to note, as another freak of mimicry, a structure resembling most excellent examples of microscopic eozoön. The microstructure of the lithoidal portion of this lava flow is the same as that of many other lithoidal rhyolites in various parts of the world.

FAYALITE.

In the porous portions of the larger spherulites, intimately crystallized with the feldspar and tridymite and generally surrounding the feldspar, as of later growth, are occasional crystals of fayalite, irregularly outlined, evidently one of the last minerals formed. They

are sometimes noticed among the coarser crystals of feldspar, quartz, and tridymite, near the cavities of the more porous layers.

It is most unusual to see so basic and ferruginous a mineral as this iron olivine intimately associated with abundant quartz and acid feldspars in a highly siliceous, volcanic rock containing less than 2 per cent. of iron oxide. It is contrary to almost universal observation, and therefore to the laws which are supposed to govern the mineral composition of igneous rocks. It is formed especially within the lithophysæ, and an explanation of its occurrence may throw some light upon the origin of these interesting structures.

ORIGIN OF FAYALITE AND LITHOPHYSÆ.

The probable origin of fayalite in so siliceous a rock as obsidian will appear from the following considerations:

MINERAL ASSOCIATION.

First. Its association with abundant quartz and tridymite and acid feldspars, with a small amount of magnetite, is not according to the laws which appear to govern the production of minerals by purely igneous fusion; for olivine is only found in igneous rocks low in silica and rich in iron and magnesia, and it is doubtful whether a purely iron olivine, like fayalite, has ever been found as an essential constituent of such rocks. At Fayal, where it has been found associated with trachyte, it would seem, from the description of Gmelin,¹ to occur as inclosed masses in the lava, for it is said to be full of bubbles in places, with the appearance of having been fused, and in the Mourne Mountains, Ireland, according to Delesse and Haughton, it occurs in drusy cavities in muscovite granite accompanied by beryl, chrysoberyl, fluorite, and topaz. The minerals accompanying olivine are usually lime-soda-feldspars, augite, and magnetite. Its occurrence in an obsidian with 75 per cent. of silica and less than 2 per cent. of iron oxide is so contrary to common experience that the observations of Gustav Rose, in 1827, on an occurrence of olivine in the obsidian of the Cerro de las Navajas, Mexico — which, as already pointed out, is similar to that at Obsidian Cliff — have been generally discredited by the most eminent petrographers.

Secondly. The chief minerals which accompany the fayalite are those which have not been reproduced artificially under the ordinary conditions of purely igneous fusion. The experiments of Messrs. Fouqué and Michel-Lévy and others have demonstrated the failure of the purely igneous fusion of the chemical constituents of quartz and the acid feldspars, orthoclase and albite, to produce crystals of these minerals similar to those found in acid rocks, though the more basic minerals have been so produced.

¹Chemische Untersuchung des Fayalits: Poggendorff, *Annalen*, 1840, vol. 51, p. 160.

Thirdly. Quartz, tridymite, orthoclase, and albite have all been reproduced artificially by heating their component elements in the presence of superheated water in a closed tube; that is, by a form of aqueo-igneous fusion. The experiments bearing most directly on the case in hand are those of Messrs. Friedel and Sarasin,¹ who heated in a closed tube basic silicate of potassium and silicate of aluminium and obtained along with hydrous silicate of potassium crystals of orthoclase and quartz and, at higher temperatures, tridymite. The orthoclase crystals were in great variety of forms, some of which correspond to those accompanying fayalite in the lithophysæ. A similar treatment of silicates of sodium and aluminium gave rise to crystals of albite; but it is remarked that these were never accompanied by either quartz or tridymite and that a mixture of the alkalis produced orthoclase alongside of albite, although never in isomorphic combinations. Here, again, we see that the artificial methods of aqueo-igneous fusion, like those of purely igneous, or dry, fusion, have failed to reproduce intermediate varieties of feldspars corresponding to the isomorphic mixtures of distinct species, which are everywhere produced in nature, and of which the feldspar already described and figured from Obsidian Cliff is an example, and it seems probable that while all the conditions attending the natural processes of crystallization may not be comprehended in the artificial methods, still the far more gradual and less violent action of the same forces, which in particular instances in nature act feebly through long periods of time, may be an essential factor in the production of the infinite gradations in the composition of the minerals formed.

The experiments of K. von Crustschoff² show that under the influence of superheated water tridymite is produced at a higher temperature than quartz. Other experiments have given both quartz and tridymite in the same closed tube.

Magnesian olivine has been produced³ by the action of steam and chloride of silicon on magnesium at a red heat under the pressure of the atmosphere, but as yet there seems to have been no attempt to reproduce iron olivine, which, however, occurs accidentally in many furnace slags. And finally magnetite⁴ has been reproduced by the action of aqueous vapor upon iron wire at high temperatures. From the foregoing we see that the minerals occurring in the lithophysæ at Obsidian Cliff are such as may be formed from a mixture of silicates under the influence of superheated water or steam.

Fourthly. The experiments of Mr. Daubrée⁵ upon the effect of super-

¹ Bull. Soc. minéralogie, 1879, vol. 2, p. 158; *ibid.*, 1880, vol. 3, p. 171; Comptes rendus Acad. sci., Paris, 1881, vol. 92, p. 1374; *ibid.*, 1883, vol. 97, pp. 290-294.

² Am. Chemist, 1883; Tschermaks mineral. Mittheil., vol. 4, p. 536.

³ Stanislas Meunier: Comptes rendus Acad. sci., Paris, vol. 93, 1881, p. 737.

⁴ De Haldat: Annales chimie, vol. 46, p. 70; Neues Jahrbuch für Mineral. 1833, p. 680.

⁵ Études synthétiques etc. Paris, 1879, pp. 154-179.

heated water on glass are of special interest in this connection. A sealed glass tube which contained only water was inclosed in an iron case also containing water, which was sealed and heated to redness for different lengths of time with differing results. Under certain conditions, part of the glass, a silicate of lime and soda, with 5 per cent. of alumina, was converted into a hydrous silicate, accompanied by a considerable increase of volume; part was reduced to a white, opaque mass distinctly fibrous, with a delicate banding parallel to the surface of the glass tube and resembling agate.

The surface of the tube in places was warped, blistered, and ex-coriated and frequently full of cracks, besides which a delicate foliation parallel to the surface of the glass was developed. In some instances the whole mass was reduced to powder. Examined under the microscope the altered glass showed minute nearly opaque spherulites, acicular microlites, small crystals and grains of pyroxene (diopside), and larger spherulites of a material like chalcedony. The surface of the glass was covered with prismatic crystals of quartz.

The correspondence of many of these characters with those observed in the obsidian of Obsidian Cliff is very striking and suggestive. The fibrous and delicately banded structure is similar to that of the smaller spherulites in the obsidian; the thin foliation, the gaping cracks, and encrusting quartzes are features characteristic of the lithophysæ. The microscopic forms of crystallization, though of different mineral nature, bear a great similarity, considering the difference in the chemical composition of the two glasses. Mr. Daubrée calls attention to the large amount of alteration produced in the glass by a small amount of water, scarcely one-third of the weight of the glass.

The question then arises whether water was present in the molten obsidian during the crystallization of the spherulites, and, if so, to what extent.

As already pointed out, the larger spherulites composed of rays of feldspar and a cement of tridymite are filled with gas cavities, easily recognized by their spherical shape and behavior toward light. The smaller spherulites are often clouded with minute particles, which it was suggested were partly gas cavities. That this is the case is shown by the following experiment: A fragment of a small blue spherulite was heated in the flame of an oxyhydrogen blow-pipe till it melted, when portions of it puffed up into a pumiceous glass by the expansion of the inclosed gas. The same experiment was repeated on the compact, black obsidian itself. When melted it also puffed up to a light-gray glass full of comparatively large gas cavities, quite identical with the pumice which is found on the top of this obsidian flow. This shows that the vapor which escaped from that portion of the lava that was on the surface and only subjected

to the pressure of the atmosphere was imprisoned in the deeper portions of the obsidian, probably combined with the glass, since the microscope fails to detect it.

The chemical analysis of the black obsidian and that of the dark-blue spherulites show almost identical losses on ignition, in the former 0.66 per cent. and in the latter 0.33 per cent. The greater part of this is water, which has been determined directly as such, and careful analyses of the disengaged gases from other similar obsidians, made by Boussingault and Damour,¹ have shown its widespread occurrence, frequently accompanied by chlorine. It is to be noticed that a small amount of sulphur is present in the rock of Obsidian Cliff.

That the vapors existing in this obsidian were absorbed by the magma before its eruption is rendered highly probable by the experiments of Mr. Daubrée on the penetration of water through rock by capillary attraction against a counteracting pressure of steam and on the hydration of glass by superheated water. From the observations of Mr. Fouqué² at Santorin it is likely that at extremely high temperatures the elements of these vapors are dissociated.

CHEMICAL EVIDENCE.

That the absorbed vapors in the rock were the sole agents affecting the crystallization of the denser spherulites and the production of the lithophysæ will appear from a consideration of the following chemical analyses, which were made of the rock of Obsidian Cliff for Mr. Arnold Hague, in charge of the Yellowstone National Park division of the U. S. Geological Survey. No. I is a black obsidian free from spherulites; No. II, red obsidian; No. III, small, dark-blue spherulites; and No. IV, white material forming small lithophysæ in solid, black obsidian.

	I.	II.	III.	IV.
Silica, SiO ₂	74.70	75.52	76.70	78.02
Alumina, Al ₂ O ₃	13.72	14.11	12.30	11.98
Ferric oxide, Fe ₂ O ₃	1.01	1.74	1.43	1.45
Ferrous oxide, FeO	.62	.08	.....	.....
Ferric sulphide, FeS ₂ . . .	.40	.11	.....	.....
Manganous oxide, MnO...	Trace	.....	.....	.....
Lime, CaO	.78	.78	.39	.21
Magnesia, MgO.....	.14	.10	.....	.....
Soda, Na ₂ O.....	3.90	3.92	3.89	4.16
Potash, K ₂ O	4.02	3.63	4.73	3.96
Ign	.62	.39	.66	.33
	99.91	100.38	100.10	100.11
Specific gravity	2.3447	2.3421	2.383	.....

¹ Annales chimie, Paris, 4th series, vol. 29, 1873, p. 547.

² Santorin et ses éruptions, Paris, 1879, p. 232.

Analyses I and II were made by Mr. Edward Whitfield, of the chemical laboratory of the U. S. Geological Survey, and III and IV were made by Mr. S. L. Penfield, of the Sheffield Scientific School.

Nos. I and II are almost identical, with less than 1 per cent. difference in silica. The chief point of interest lies in the relative amounts of ferric oxide and ferrous oxide present, the red obsidian having nearly all the iron in the form of ferric oxide, as already noticed.

Analyses III and IV are enough alike to be duplicates. They differ from those of the rock by being a little higher in silica and the alkalis and a little lower in the other bases. They are as close as could be expected, since the materials analyzed are from different parts of the lava flow. Other analyses might lessen this slight difference.

The main facts brought out by the analyses are that the chemical composition of the spherulite is essentially the same as that of the surrounding rock; it is then nothing more than a small portion of the magma which has crystallized with a particular structure; and, further, that the lithophysæ have the same composition as the dense spherulites, which shows that the transformation of a spherulite to a lithophysa can only be a modification of its structure, a rearrangement of its minerals, without any chemical addition or loss.

This rearrangement took place through agencies within the limits of the spherule affected and disconnected from other possible sources, for perfect lithophysæ occur isolated and hermetically sealed in dense, black obsidian. But where many such spherulites adjoined one another the cavities formed sometimes connected and spread irregularly, permitting the segregation of particular minerals in different places, which has been the case in the laminated, lithoidal portion of the lava flow.

Moreover, the hollow lithophysæ were formed prior to the consolidation of the surrounding matrix, for they are occasionally found with the outer shell crushed and the viscous matrix forced part way in, showing that the mass was at a very high temperature and still viscous when the modification of the spherulites took place.

CONCLUSION.

We may fairly conclude that the lithophysæ in the obsidian of Obsidian Cliff, with their contents of prismatic quartz, tridymite, adular-like and tabular soda-orthoclase, magnetite, and well crystallized fayalite, are of aqueo-igneous origin and result from the action of absorbed vapors upon the molten glass from which they were liberated during the process of crystallization consequent upon cooling.

Apparent exceptions.—Cavities and lithophysæ occur, over which a distinct arching of the lamellæ of the lithoidal rock is observed, the layers apparently accommodating themselves to the swelling of the hollows beneath; some appear simply as cavities coated with crystals

of quartz, feldspar, and associated minerals; others have the concentric chambered structure of lithophysæ (Pl. XIV, Fig. 7). The same phenomena have been described by Prof. F. Zirkel in the lithoidite from the southeast shore of Taupo Lake, New Zealand. The hollow spaces in that rock are intersected by partition walls coated with crystals of quartz, feldspar, hornblende, and mica and in many ways correspond to the lithophysæ of Obsidian Cliff. At first sight it would seem that the expansion of a bubble of gas within the lava had occasioned the distention or displacement of its layers, but a careful study of portions of the rock which exhibit great contortion and plication of the layers makes it evident that in these cases the hollows occur beneath arches in the folds where there has been a local relief or diminution of pressure, which might allow the absorbed vapors to disengage themselves and bring about the conditions which produce hollow lithophysæ in connection with spherulitic development. In other words, the arching of the layers appears to have been the cause of the liberation of gases and the production of the cavity beneath, and not the result of expanding gases.

That such local inequalities of the layers could have existed within the plastic mass is evident from the fact that the moving lava was so viscous and stiff before its final halting that, as already noticed, in one place where the layers of flow reached a vertical position they pulled apart and solidified with gaping crevices between, the surfaces of the separate slabs consisting of stony fragments on a ropy, corrugated glass.

DEVELOPMENT OF VARIOUS STRUCTURES IN OBSIDIAN.

The development of the various forms of structure exhibited in this obsidian flow may be summed up as follows:

The molten mass when it reached the surface at the time of eruption was a viscous glass, highly siliceous and slightly hydrated or holding certain gases absorbed in it. Those in the glass at the top of the mass immediately expanded, being relieved of the pressure to which they had been subjected, and the glass chilled quickly into pumice. A little lower in the mass the expansion of the gas was but slight, filling the glass with small bubbles. In the compacter glass, which cooled more slowly than the pumice, trichites and microlites formed. After these the microscopic groups of feldspar and quartz with pegmatoid and fibrous structure crystallized; this must have been under the influence of the absorbed vapors at a high temperature, since they have not as yet been produced artificially by dry fusion.

Undoubtedly particular conditions of temperature, pressure, and consequent rate of cooling obtained in different parts of the flow at different stages of its progress, but about the time it came to rest in the region of Obsidian Cliff small colorless spherulites and fibrous

coatings around the granophyre groups were formed under conditions differing from those attending the production of the granophyre groups by the influence of a slightly lower temperature. In these the free silica would still seem to be quartz. In the next stage small colored spherulites crystallized with a fibrous structure in sectors of various orientation, which also appear to be composed of feldspar and quartz inclosing trichites and microlites.

With progressive cooling the nature of the spherulites passed to those whose centers are similar to the small ones just described, but the outer portion of which is formed of rays of short, attached feldspar crystals cemented with tridymite, the whole imprisoning multitudes of minute gas cavities. The absorbed vapors now began to assume the rôle of superheated water in their action on the surrounding silicates, which is more evident in the hollower forms, where the process appears to have been somewhat as follows: In the still viscous glass, from a center of crystallization the first frail beginnings of feldspar spread in innumerable rays, pre-empting, as it were, a sphere of the magma. The enlargement of these anhydrous microlites by crystal growth from their matrix of hydrated glass not only altered its chemical constitution by eliminating the alumina and the alkalis, but rendered it relatively more hydrous, so that, with decreasing temperature, it may no longer have been able to retain the vapors in combination.

The vapors separated from the glass were probably disseminated in minute particles through it, in some cases being able to coalesce into larger bubbles or to accumulate in certain parts of the spherule. A prolonged action of this sort permitted the separation of the original paste into feldspar, iron silicates and oxides, and residual silica, which at high temperatures would take the form of tridymite, but at lower temperatures would crystallize as pyramidal and prismatic quartz; a change of temperature or an intermediate one would cause both tridymite and quartz to crystallize.

The first crystallized feldspars were suspended in a plastic, hydrous silicate, which, from the observations of Mr. Daubrée, would occupy considerably greater volume than the same siliceous glass if anhydrous, and therefore still more than its component elements when crystallized. Upon the change of the hydrous paste to a crystalline aggregate through the process above indicated there would be considerable shrinkage, the extent of which is indicated by the gaping cracks and parted segments characteristic of lithophysæ. This shrinkage was prior to the ultimate crystallization of the cementing paste, for the surfaces of the disrupted portions are coated with well developed crystals of fayalite, tridymite, and quartz. The tendency observed in spherulitic crystallization to produce concentric layers of different texture, which in the compact spherulites results in bands of greater or less density and of various colors, in the hollow

varieties gives rise to the concentric shells of typical lithophysæ, by producing layers which act as nuclei about which the later-formed minerals, tridymite, quartz, and fayalite, crystallize, leaving cavities in place of the porous layers of the more solid spherulites.

CONDITIONS MODIFYING THE DEVELOPMENT OF LITHOPHYSÆ.

Finally, the occurrence of lithophysæ in a rock, the nature of their contents, and the extent to which the cavities are developed (that is, their relative size) will depend on a number of conditions, first among which are unquestionably the character and chemical composition of the molten lava, the degree of hydration, and nature of the absorbed gases, and, second, the rate of cooling and the pressure under which consolidation takes place, for it is evident that under the same physical conditions glasses of different chemical composition will be affected differently by the same amount of absorbed gases. So far observations indicate that only the acid glasses produce these hollow spherulites. The amount of water vapor and the nature of the gases associated with it will alter both the extent of the action and the character of the minerals formed. With a given combination of these primary conditions, the results will vary with the rate of cooling and with the pressure, too rapid cooling not giving time enough for any crystallization to take place, too low a pressure permitting the gases to escape suddenly, and too high a pressure preventing their liberation in the proper state to produce the effects observed in lithophysæ, and bringing about with the consequent slower cooling a granular, crystalline structure, the grains of which inclose the imprisoned gases condensed to a liquid form.

THE CAUSE OF DIFFERENT LAYERS IN LAMINATION.

In an earlier part of this paper attention was called to the parallel lamination of the rock, specially noticeable in the lithoidal portion. It was referred to slight local differences in the consistency or composition of the lava, which in flowing over the surface in a viscous condition spread these differing portions out in layers parallel to the plane of flow. A cause for such local differences is suggested by the following observations: In the lithoidite the layers vary in their degree of crystallization, some being glassy, others finely spherulitic, others more coarsely spherulitic and porous, while still others are quite granular and full of cavities; some glassy layers have the crystallization localized in spherulites and lithophysæ. These alternate and repeat themselves in endless succession and variety. In the obsidian the differences find expression in layers of spherulites, large and small, and bands of lithophysæ, and in layers varying in the abundance of granophyre feldspars, microscopic spherulites, mi-

crolites, and trichites; that is, in the different phases and amount of crystallization developed. Approaching the surface of the flow the same laminated condition of the rock appears in still more striking differences between the amount of microlites present and in layers of gas cavities which produce alternating bands of vesicular and dense glass and pumice, until at the surface the whole mass is thoroughly pumiceous.

It is evident that there is a difference in the amount of vapor absorbed in layers of the rock, which is shown by the varying extent to which the layers are inflated when the pressure is removed and the confined gases are allowed to expand.

From the part which superheated water has undoubtedly played in the development of lithophysæ and the larger spherulites, from the aqueo-igneous conditions deemed necessary for the production of the granophyre groups of quartz and feldspar, and, finally, from the observed changes of plasticity produced in a siliceous glass by hydration, it seems highly probable that the differences in consistency and in the phases of crystallization here developed are directly due to the amount of vapors absorbed in the various layers and to their mineralizing influence.

Besides the lamination of the pumiceous portion of the rock, which proves that the absorbed vapors were distributed unequally in alternating layers, there are highly pumiceous or inflated spots scattered through the mass, which show that the vapors were more abundant also in certain spots than in others. The distribution of these inflated spots corresponds to that of the isolated lithophysæ and spherulites throughout the rock.

HISTORICAL REVIEW.

Having attempted an explanation of the nature and origin of lithophysæ which seems to accord most closely with the phenomena of their occurrence at Obsidian Cliff, it will be of interest to review the opinions of those who have studied the question in other fields and upon different material.

Ferdinand von Richthofen.—The first notice of these curious rock structures is the very full and graphic description of those found in the rhyolites of Hungary, given by von Richthofen¹ more than twenty-five years ago, at which time he proposed the name of Lithophysen, because the rock appeared to have been inflated by the expanding of gas. He considered them quite distinct from spherulites and said that only through the most careful chemical analysis could positive conclusions as to the process of their formation be reached. He thought that a gas had been evolved, for the oft-repeated, lam-

¹Studien aus den ungarisch-siebenbürgischen Trachytgebirgen: Jahrbuch k. k. geol. Reichsanstalt, vol. 11, 1860, p. 180.

ellar banding of the surrounding rock showed that it had been forced apart, not violently but gradually, since the separate layers of the rock bent themselves exactly to the curvature of the hollows. Moreover the gas had been evolved from the inclosed substance for the hollow spaces are found only in connection with this and do not occur by themselves in the groundmass. Further, they have come into existence after the laminated arrangement of the rock; consequently the gas must have been connected with the inclosed substance in either a solid or fluid condition. From the form of the repeated shells within the lithophysæ it would appear that their substance was exceedingly viscous at the time the gas was set free. The question then suggests itself how and for what reason was the substance of the incision separated out of the rock and what sort of gas was evolved. He thought that the experiments of Daubrée threw some light on the process. They showed, he said, that water at a temperature of 400° C. under high pressure dissolves all the constituents of glass and upon cooling deposits them as different crystals, in part anhydrous. He referred to the effect of hydration in increasing the fluidity of lavas and added that, if in consequence of this any hydrate had been developed in particular parts of the rock, then the process already suggested would easily take place, for a part of the water could no longer remain in combination, because of the lessening of pressure upon the eruption of the rock, and would disengage itself as gas. It would force the viscous rock mass apart, but could not escape, and thus the forms in question must have been produced.

With this view, expressed by von Richthofen in the early days of the science of microscopical petrography, that of the present paper is in accord at many essential points; but the earlier view represents bubbles of gas expanding from their point of liberation within the viscous lava and forcing back the surrounding matrix; they carry up successive films of the plastic glass and thus produce concentric shells. The objections to this are the physical difficulty of expansion under the circumstances and the radially fibrous structure observed in connection with the often incomplete shells, which correlate them with the concentric layers of spherulites.

Dr. Joseph Szabó,¹ in a paper on the trachytes and rhyolites in the vicinity of Tokay, Hungary, expresses the opinion that lithophysæ are only a stage in the mechanical and chemical alteration of spherulites, which through chemical alteration first lose their luster and then their coherence. He thinks the bases are removed chemically, the insoluble particles mechanically, and that the silica is concentrated in the cavity.

¹ Die Trachyte und Rhyolite der Umgebung von Tokaj: Jahrbuch k. k. geol. Reichsanstalt, vol. 16, 1866, p. 89.

*Karl Ritter von Hauer*¹ published in the same year the results of the chemical analyses of four rhyolites which carry lithophysæ, and also of the substance of the lithophysæ. They are given further on, in the table of chemical analyses (p. 43). They show that the lithophysæ do not differ chemically from the groundmass which contains them and give some idea, he said, of their mode of origin. He thought that the lithophysæ were separated out from the groundmass only in a mechanical way through the development of gas, and not as the product of metamorphosing influences on the groundmass; that the gases (in this case water vapor), upon being evolved in the still viscous mass, were able to find exit only slowly and occasionally not at all; in this way pores, larger hollows, and bladder-like inflations were produced.

*Justus Roth*² in 1869 adopted Szabó's views that lithophysæ are only mechanical and chemical alterations of spherulites and repeats them in his *Allgemeine und chemische Geologie*, 1883, vol. 2, p. 216.

Ferdinand Zirkel,³ in describing the rhyolites in the collection of the Geological Exploration of the Fortieth Parallel, calls attention to spherulites in the rock from Shoshone Mesa, which "develop, by decomposition, a concentric layer-structure." These he considers to be the same as the lithophysæ of von Richthofen and that they in like manner were only the result of chemical alteration.

*Ch. E. Weiss*⁴ considers the cavity of a hollow spherulite as playing the same rôle as a solid body around which the spherulite forms. He thinks hollow spherulites and hollow spheres are only larger and smaller spherulites which have formed around gas bubbles; where several bubbles were near together and touched one another there arose the chambered, hollow spherulites, or lithophysæ. The coarser-grained spherulites, he says, show they are composed of two minerals, quartz and feldspar.

*Grenville A. J. Cole*⁵ reviews the previous opinions on the subject and concludes that the hollows are due to the decomposition of solid spherulites by chemical agents, the material having been carried out through cracks in the rock.

*C. A. Tenne*⁶ describes the lithophysæ in the obsidian from Cerro de las Navajas, Mexico, collected by von Humboldt, to which von

¹ Die Gesteine mit Lithophysenbildungen von Telki-Banya in Ungarn: Verhandl. k. k. geol. Reichsanstalt, 1866, p. 98.

² Beiträge zur Petrographie der plutonischen Gesteine, 1869, p. 168.

³ U. S. Geol. Ex. Fortieth Par., vol. 6, Microscopical Petrography, 1876, p. 212.

⁴ Quartzporphyren aus Thüringen: Zeitschr. Deutsch. geol. Gesell., Berlin, vol. 29, 1877, p. 418.

⁵ On hollow spherulites and their occurrence in ancient British lavas: Quart. Jour. Geol. Soc. London, May, 1885.

⁶ Ueber Gesteine des Cerro de las Navajas (Messerberg) in Mexico: Zeitschr. Deutsch. geol. Gesell., Berlin, 1885, p. 610.

Richthofen calls attention in the paper already cited and from which Rose obtained the olivine crystals. He says that the substance of the lithophysæ must be devitrified obsidian, which a microscopical investigation makes probable. He gives chemical analyses (see analyses VII and VIII, next page) which show that the obsidian and lithophysæ have the same chemical composition.

Whitman Cross,¹ in a paper "On the occurrence of topaz and garnet in lithophyses of rhyolite," points out the fact that these minerals are not of secondary formation in the cavities, but primary, "produced by sublimation or crystallization from presumably heated solutions, contemporaneous or nearly so with the final consolidation of the rock. The lithophysal cavities seem plainly caused by the expansive tendency of confined gases or vapors, while the shrinkage cracks in the walls and white masses of the Nathrop rock suggest the former presence of moisture. Certainly the history of the lithophyses themselves embraces that of both topaz and garnet."

From this it is seen that two distinct views of the origin of cavities within the lithophysæ have been taken: One, that the hollows were of primary origin, formed while the lava was still plastic, and were due to inclosed gases or vapors. Among those who held this opinion some considered the lithophysæ as wholly distinct from spherulites, while others thought them simply hollow varieties of spherulites. The second view was that the hollows had been produced in solid spherulites by chemical decomposition and alteration, and were subsequent to the solidification of the lavas in which they occur.

GEOGRAPHICAL DISTRIBUTION OF OBSIDIAN.

As the thoroughly glassy forms of many varieties of rocks present much the same general appearance and are with difficulty distinguished from one another, they have all been classed together as obsidian. Thus the term has come to signify any volcanic glass which has a small percentage of water and is almost if not wholly free from porphyritic crystals. But since the more siliceous rocks have a greater tendency to cool as glasses than the basic ones, most of the volcanic glasses belong to acid rocks. They may range from less than 60 per cent. to 78 per cent. of silica, including a few basalts with some andesites and trachytes and all dacites and rhyolites. The rock forming Obsidian Cliff is a rhyolitic obsidian, and on the next page is given a table of chemical analyses of similar rhyolitic obsidian from widely distant parts of the world, together with the analyses of spherulites and lithophysæ found in some of them. The analyses of rhyolite and lithophysæ made by Karl von Hauer are placed side by side for comparison.*

¹ Am. Jour. Sci., 3d series, vol. 31, 1886, p. 432.

- I. Black obsidian free from spherulites, Obsidian Cliff, Yellowstone National Park.
- II. Red obsidian free from spherulites, Obsidian Cliff, Yellowstone National Park.
- III. Small, dark-blue spherulites, Obsidian Cliff, Yellowstone National Park.
- IV. White lithophysæ from black obsidian near Lake of the Woods, Yellowstone National Park.
- V. Black obsidian with numerous gas cavities (Russell), Mono Lake, California.
- VI. Black obsidian, Obsidian Hill, Tewan Mountains, New Mexico.
- VII. Black obsidian (Tenne), Cerro de las Navajas, Mexico.
- VIII. Lithophysæ from the same (Tenne), Cerro de las Navajas, Mexico.
- IX. Obsidian (Abich), Lipari Islands.
- X. Rhyolite (K. von Hauer), Goenczer Pass, Hungary.
- XI. Rhyolite (K. von Hauer), Telki-Banya, Hungary.
- XII. Rhyolite (K. von Hauer), south of the Neue Massamühle, Telki-Banya, Hungary.
- XIII. Rhyolite (K. von Hauer), south of the Alte Massamühle, Telki-Banya, Hungary.
- XIV. Contents of the lithophysæ in the last-mentioned rhyolite.

Constituents.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.
SiO ₂	74.70	75.52	76.70	78.02	74.05	76.20	75.23	75.64	74.05	77.03	76.34	76.80	75.55	75.91
TiO ₂						Trace								
Al ₂ O ₃	13.72	14.11	12.30	11.98	13.85	13.17	12.36	12.68	12.97	12.77	13.22	12.18	15.65	14.98
Fe ₂ O ₃	1.01	1.74	1.43	1.45	Trace	.34	.96	1.07	2.73	1.92	1.93	1.56		
FeO	.62	.08				.73	1.24							
FeS ₂	.40	.11												
MnO	Trace					.10				Trace	Trace	Trace	Trace	Trace
CaO	.78	.78	.39	.21	.90	.42	1.00	.83	.12	1.45	1.85	1.07	1.09	.94
MgO	.14	.10			.07	.19	.01	Trace	.28	.31	.21	.20	.34	.34
Na ₂ O	3.90	3.92	3.89	4.16	4.60	4.31	4.00	4.98	4.15	2.97	2.84	2.82	6.61	3.36
K ₂ O	4.02	3.63	4.73	3.96	4.31	4.46	4.62	3.51	5.11	4.13	3.67	4.50		3.07
P ₂ O ₅							.27		.31					
H ₂ O						.33				.74	.61	.89	.76	1.30
Ignition	.62	.39	.66	.33	2.20		.73	1.58	.22					
	99.91	100.38	100.10	100.11	99.98	100.25	100.42	100.29	99.94	101.32	100.67	100.02	100.00	99.90
Sp. gr.	2.3447	2.3421	2.383			2.352			2.370	2.410	2.403			2.420

Obsidian with more or less porphyritic crystals occurs over large areas in the Yellowstone Park; it abounds in spherulites and lithophysæ, which are also found in the pearlites and rhyolites of the same region. Lithophysæ also occur in the dark, pearlitic rhyolite from the base of the cliff of Shoshone Mesa, near Rock Creek, Idaho, where they were collected by Mr. S. F. Emmons,¹ who says they “are generally hollow and look like a clayey mass formerly filled with gaseous matter which has burst forth leaving a hollow interior. * * *

The centers of some of the lithophysæ are still filled with crystals of quartz and feldspar.”

¹ U. S. Geol. Ex. Fortieth Par., vol. 2, Descr. Geol., p. 615.

A well known locality for obsidian is Mono Lake, California, where a chain of extinct volcanic cones stretches southward from the lake. They are mainly composed of rhyolitic pumice in vast flows, with which are associated large outbursts of obsidian. This obsidian is a black glass without porphyritic crystals. Thin sections of the obsidian from the first and second large craters south of Mono Lake, which were collected by Mr. Arnold Hague, show it to be a clear glass, free from microlites and trichites. Its chemical composition, given in analysis V of the table, which was made for Mr. I. C. Russell, is almost identical with that of the black obsidian of Obsidian Cliff, except that there is only a trace of iron and over 2 per cent. loss by ignition. The obsidian passes into vesicular and bubbly glass and pumice; in places multitudes of minute bubbles produce gray bands through the black glass, which in certain lights show a beautiful luster and heliotrope color. From the highest volcanic cone at the south end of Mono Lake Mr. George M. Wright collected obsidian full of small, blue spherulites, among which are scattered larger ones about an inch in diameter.

Very beautiful, black obsidian, with small lithophysæ and occasional spherulites, occurs at Obsidian Hill and on the Rio San Diego and in other localities in the Tewan Mountains, New Mexico, where it has been collected by Maj. J. W. Powell, Director of the U. S. Geological Survey, and by Mr. William H. Holmes. This obsidian is remarkably transparent in thin fragments, but is intensely black in larger pieces; it is almost free from microscopic secretions, there being only a small amount of black grains, probably magnetite, and a few microscopic feldspars. Chemical analysis, No. VI, of the obsidian, from Obsidian Hill, N. Mex., shows that it has very nearly the same chemical composition as the obsidian of Obsidian Cliff, with slightly more silica and less iron oxide, which may account for the absence of fayalite from the lithophysæ of the former.

Near Coyote Spring, 30 miles north of Milford, Utah, Mr. G. K. Gilbert found obsidian closely resembling that at Obsidian Cliff. It is black, variegated with red and brown, some of it being very transparent in comparatively thick pieces. It is spherulitic and free from porphyritic crystals. Associated with it are pumice, lithoidite, and porphyritic rhyolite. Through the kindness of Mr. George P. Merrill, of the National Museum, the writer has been able to look over the collections of obsidian from the Western States and Territories and some foreign localities and make such notes as he desired.

From Beaver Valley, Utah, Mr. I. C. Russell has collected spherulitic, black obsidian, the spherulites having a curious, ragged form, probably consisting of a cluster of smaller ones. At White Mountain, Utah, a black obsidian occurs which is full of light-gray lithophysæ. Black obsidian without porphyritic crystals has also been brought in from High Rock Cañon, Nevada, and a black perlite from

Trout Creek Point, on the crest of Quinn River Mountains, Nevada. This rock is crowded with dark red and brown spherulites of considerable size; it contains 75.50 per cent. of silica.

Black obsidian more or less spherulitic has been found at White Sulphur Springs, Napa County, and in the Pitt River district, California, the latter locality furnishing beautifully banded and mottled varieties.

Glass Butte, Oregon, is formed of a fine, red, brown, and black obsidian, specimens of which were collected by Mr. I. C. Russell. Some of the black is very transparent and clear, with a smoke-brown tinge in thin pieces; through it are scattered small white spherulites.

One of the purest obsidians known, according to Professor Zirkel,¹ occurs in the form of kernels and balls in the pearlite of Grass Cañon, Nevada, which has been described by Mr. Arnold Hague.² The obsidian balls are from half an inch to an inch in diameter and are associated with a white, pumiceous tufa inclosing fragments of pearlite. They are intensely black in color and in thin section are gray with few black, trichitic lines. The obsidian from Cerro de las Navajas, Mexico, as already mentioned, corresponds in many ways to that of Obsidian Cliff (compare analyses VII and I). It is associated with liparite and bluish-gray, spherulitic lithoidite and carries occasional crystals of sanidine and lithophysæ. Red and black obsidian is found at the same place. At Cerro Pelado, southwest of Cerro de las Navajas, spherulitic obsidian with lithophysæ is associated with lithoidal and spherulitic rhyolite and pearlite. Similar obsidian is found at San Juan de los Llanos, Puebla.

In Ecuador, near Guamani, occur spherulitic obsidian flows. The glass is banded with dark layers which are older than the spherulites. It contains a few porphyritic crystals of sanidine and biotite and is associated with lithoidite and pumice.³

An obsidian lava rich in spherulites is described by G. vom Rath⁴ from Antisana in the Andes. The microscopic characters of the spherulites correspond closely to those of Obsidian Cliff.

The Lipari Islands, north of Sicily, are famous for the abundance of obsidian found there. It is partly spherulitic, with lithophysæ, and is intimately associated with pumice. Analysis IX, published by Abich, is of obsidian from this locality. At Monte Guardia a gray, porous, and pumiceous rock contains exceedingly numerous, thin strips of black obsidian, which are parallel to the direction of the lava flow.

Another celebrated locality is Iceland, where the obsidian, judg-

¹U. S. Geol. Ex. Fortieth Par., vol. 6, Microscopical Petrography, 1876, p. 210.

²Ibid, vol. 2, Descr. Geol., p. 784.

³J. Roth: Monatsber. k. preuss. Akad. Wiss., Berlin, 1874, p. 379.

⁴Zeitschr. Deutsch. geol. Gesell., Berlin, vol. 27, 1875, pp. 296-302, 341-343.

ing from its chemical composition, belongs rather to dacite. The flow at Hrafninnuhryggr is banded by alternating layers of crystalline and glassy rock.

It is not very abundant in Hungary, but occurs in the Caucasus, on Teneriffe, Ascension, and Guadeloupe, in Java, and Japan.

In New Zealand,¹ on the southeast shore of Rotorua Lake, spherulitic obsidian is found which is dark-grayish brown in thick masses; in thin splinters it is as clear as water or has a light tinge of smoky gray. In it lie sharply defined, small spherulites with a bluish-gray, waxy luster. The obsidian has 75.03 per cent. silica and the spherulites have 74.55 per cent.

Black obsidian is very abundant on Tuhua Island, Bay of Plenty, *tuhua* being the South Sea Islander's word for obsidian. Pieces often have a silvery or iridescent coating like that produced on artificial glass by the decomposing action of the atmosphere. Its silica percentage is 74.91.

Behind the village of Totara, on the southeast shore of Taupo Lake, stands a vertical wall of lithoidite with most remarkable lamellar structure and regular columnar parting. The lamellæ are of almost microscopic thinness, principally in two colors, a grayish-black and purplish-gray, of which there are many lighter and darker shades, alternating with one another like the banding of an agate. Occasionally bubble-like distensions are observed, in the neighborhood of which the lamellæ of the rock thin out. The cavities are mostly flattened in the plane of the lamellæ. The interior is often interrupted by partition walls, which are coated with minute crystals, probably of quartz and feldspar, with hornblende and thin flakes of mica. The rock corresponds very closely to the lithoidite at Obsidian Cliff, except for a few porphyritic crystals of quartz and feldspar and a slightly lower percentage of silica, 70.67.

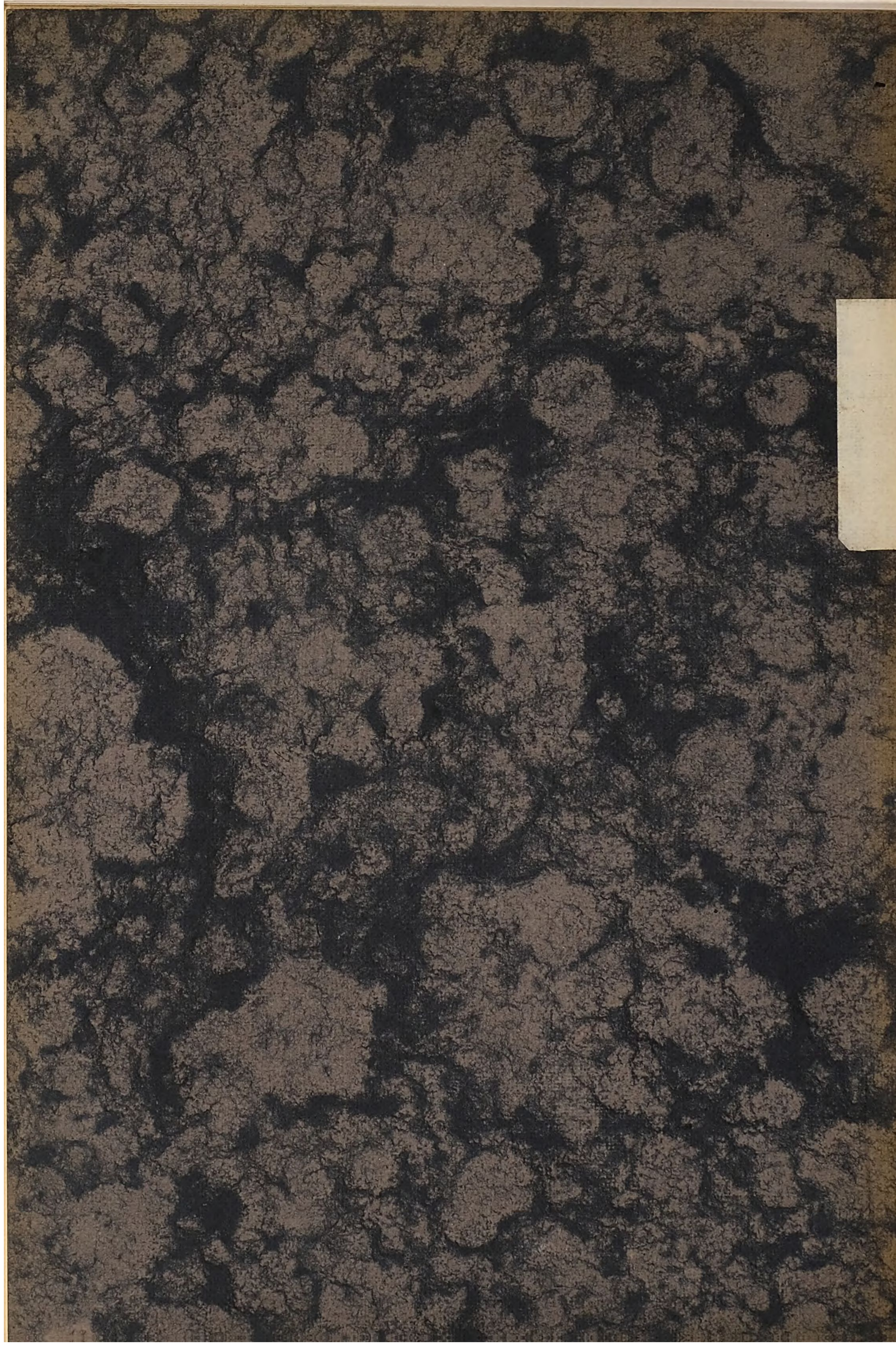
CONCLUSION.

In conclusion, we see that obsidian of nearly the same chemical composition and microstructure occurs in all parts of the world; that it is generally accompanied by like modifications, passing into pumice on the one hand and into lithoidal or porphyritic rhyolite on the other; and that in most instances it is more or less spherulitic. But the obsidian flow a part of which forms Obsidian Cliff is especially remarkable for its extent and thickness, which exceed those of any other described locality, unless surpassed by some occurrences in Mexico. It is, so far as we are able to learn, the only occurrence of rhyolitic obsidian in which a distinctly columnar structure has been developed. It is entirely free from porphyritic crystals and abounds in spherulitic structures and lithophysæ of great beauty

¹F. Zirkel: Petrographische Untersuchungen über rhyolitische Gesteine der Taupo-Zone; F. v. Hochstetter: Geologie von Neu-Seeland, 1864.

and perfection. The absolute freshness of the rock and absence of secondary alteration permit the study of these forms of crystallization without confusion with decomposition-products or subsequent metamorphism, common in older and more crystalline rocks, or even in recent lavas which have been attacked by solfataric or hot-spring agencies, as those in many parts of the Yellowstone Park have been, where the effects of secondary alteration are easily recognized. They leave no doubt that the spherulites and lithophysæ, in all their complexity of form and structure, are of primary crystallization out of a molten glass, which was gradually cooling and consolidating, and that, since its solidification, no alteration, chemical or mechanical, has taken place.





Iddings, Joseph Paxson

Obsidian Cliff, Yellowstone National Park By Joseph P. Iddings

[s.l.] [1889]

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